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Homeostatic control, smart metering and efficient energy supply and consumption criteria: A means to building more sustainable hybrid micro-generation systems

Franco Fernando Yanine *,1, Federico I. Caballero [1], Enzo E. Sauma [2], Felisa M. Córdova [3]

School of Engineering, Faculty of Engineering of the Pontificia Universidad Católica de Chile (PUC), Campus San Joaquin, Avda. Vicuña Mackenna 4860, Comuna de Macul, Santiago, Chile

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ABSTRACT

This paper presents an innovative approach for the understanding and control of grid-connected hybrid micro-generation systems (HMS) without energy storage, to supply electricity to a group of homes designated as 'Sustainable block'. The initiative is based on an effort to integrate non-conventional renewable energies (NCRE) through distributed generation (DG) projects intended for remote and rural communities in Chile and South America, where electricity supply is both expensive and often times unreliable. This may be due to equipment malfunction, line faults and/or harsh climatic conditions or other natural phenomena like earthquakes, all of which can undermine the electric power distribution networks. Here a systems thinking (ST) and cybernetics approach is employed which looks at grid-connected microgrids supplying power to local loads as intrinsically dynamic, complex adaptive systems (CAS). Moreover, such systems can be viewed and approached as a complex sociotechnical system, wherein the energy users ought to play a crucial role as 'active loads' within the sustainable block to which the grid-tie microgrid is coupled. Building upon this theoretical framework, a set of coordination and supervisory control strategies for renewable microgrids is presented based on homeostatic control (HC) principles introduced by Schweppe et al. Homeostatic control of power systems. In: Fourth energy monitoring and control system conference. Norfolk, VA: November; 1979. The approach is intended to study and eventually develop new forms of sustainable renewable energy technologies (RETs) for DG of electricity and heat, working in parallel with the grid and offering new choices and benefits to energy users everywhere. A concrete theoretical model is proposed and the algorithms depicting the strategies are explained and compared through simulation analysis.

Unlike what is available in the literature on sustainability, and looking at what is missing in regards to HMS as sustainable energy systems (SES), this paper offers an entirely new and significant perspective in terms of design and operation of such systems. First the concepts of sustainability and SES applied to HMS are explored, finding that the large majority of the mainstream analysis reviewed on the subject is focused on socio-economic, environmental, and regulatory issues rather than on the systemic, technical and operational aspects of such systems, as this paper does, and how HC, energy efficiency (EE), and a novel approach to energy supply and consumption equilibrium based on homeostasis can help build more sustainable HMS. Results are presented which confirm the hypotheses underlying the strategies employed and the model predictability, showing that SES are indeed possible and feasible. Discussion and recommendations are also offered stressing the fact that sustainability is essentially a systemic property and operational in nature, rather than explained by exogenous factors.

* Corresponding authors.
E-mail address: fyanine@uc.cl (F.F. Yanine).

[1] Graduate Researcher at the School of Engineering of Pontificia Universidad Católica de Chile (PUC).
[2] Associate Professor at the Dept. of Industrial & Systems Engineering of the School of Engineering, PUC.
[3] Professor at the Dept. of Industrial Engineering; Faculty of Engineering of Universidad de Santiago de Chile, USACH.

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1. Introduction

Homeostatic control is a term first introduced by Schweppe and his group of collaborators at MIT back in 1979 and in early 1980s [1–6] which stems from their highly visionary work and insight regarding both, flexibility and stability in electric power systems (EPS) linked to homeostasis, understood as reaching and maintaining an efficient equilibrium state between energy supply and demand, considering the diverse nature and operation dynamics of the wide variety of industrial and commercial loads [1–6]. Their approach advocated homeostatic control (HC) of energy supply and demand in an effort to make utilities power supply more efficient, particularly when supplying large industrial and commercial customers. Indeed Schweppe and his group were much ahead of their time, having had a true insight for what was to come in the years ahead, anticipating also the need for new control technologies and energy management systems to adequately manage the intermittent supply of RETs (mostly wind back then) and how to best fit these RETs in the current electric power infrastructure [7–11]. Something that we are still dealing with today. HC is based on the idea that homeostatic regulation (HR) and control mechanisms apply in EPS management when viewed as dynamically complex adaptive systems [12,13]. In fact a grid-connected microgrid supplying energy to a group of residential consumers somewhere, where the energy users have access to all the relevant information regarding the microgrid's supply, the grid’s provision of electricity and their energy usage dynamics, constitute indeed a complex, dynamic sociotechnical system in itself [14]. Such sociotechnical system is a CAS in transition to a new order in terms of its energy management and efficient equilibrium between energy intake and expenditure [8–10,12–14].

On the other hand sustainability is the capacity of a living system to endure and survive in spite of changes within or outside of the system. It is inherent to all living systems – just like homeostasis is – whether they are open or closed. Understanding this concept is basic for the effective development of sustainable energy system (SES) and important for building more robust and efficient EPS in the future [7–11]. Unlike most of the work done up to the present on the subject of sustainability and sustainable energy systems – which largely pertains to economic, environmental, social and regulatory issues – this paper focuses rather on the concept of built-in sustainability in hybrid energy systems (HES). Hence, departing from the main stream analysis of sustainability in micro-generation power systems in particular, the paper explores the technical and operational aspects of such systems and how homeostatic control (HC) principles, energy efficiency (EE) and a novel approach to managing energy supply and consumption towards efficient equilibrium can help build more sustainable hybrid micro-generation systems (HMS).

Upon reviewing the subject one finds that most of the literature dealing with sustainability and SES addresses the classical issues on sustainability in regards to energy systems design and management, somehow overlooking the more systemic, technical and operational aspects of SES linked to HR mechanisms and HC (see Fig. 5 on [9]), somehow lacking an in-depth analysis of the participating systems interaction from a systemic and cybernetics viewpoint [15]. Thus one finds that much of the work done up to the present on the subject matter focuses on economic, environmental, social and regulatory issues, somehow overlooking key operational and technical aspects of SES. This becomes particularly relevant when it comes to micro-generation power systems and their inherent sustainability. Such classical views of SES look rather at the sources of energy, making economical and environmental considerations the pivotal factors in the decision making process, and favoring the use of energy derived from renewable energy sources (RES) 100% whenever possible. This is particularly evident when reviewing the literature on such topics as communitarian cooperativism in HMS implementation and sustainability indicators in rural electrification [16,17], or reducing energy demand using demand side management (DSM) programs in targeted areas through all kinds of action plans, policies and regulations as it is being done in highly populated regions like India [18]. Yet using 100% renewables is not always possible or even convenient. Thus a proper combination of RES-based technologies and conventional energy sources is used in such cases [7], along with an adequate design and configuration of the grid-connected HMS where RES and the grid supply play a crucial role [7–11,19–26]. This should be accompanied by a proper system design, dimensioning and management of the loads (demand for energy and how it is expended), EE considerations in such designs, and the use of feedback [19–33] in a way that the entire system is made as efficient, productive and sustainable as possible in terms of energy supply and demand considering various factors and constraints [33–36]. Such views even go as far as suggesting that “there is a need of an energy ethics: a moral obligation to deal with the energy problems at the center of that decision making process” [37] and also introduce all kinds of social, economic and environmental

considerations over technical and operational ones, as if sustainability could be explained by exogenous factors [38]. Sustainable energy practices and technologies are important in modern society but they are not a "*moral obligation*" to be kept as a beacon for safeguarding the world's energy future. Sustainability is eminently both a technical and an operational issue and it is systemic in nature, meaning that an energy systems engineering approach must be adopted, especially at the decision making stages, regarding the design and planning of the system itself and the way we use and manage energy supply in such a way that EE and productiveness of such systems are core capabilities [39–49]. This encompasses several factors within the scope of SES. The view presented here overlooks the classical rhetoric that so many authors have employed when looking to address sustainability turning it into a reality based on regulations and policy issues; presenting ethical and socio-economic challenges that require an inclusive and holistic approach that transcends the traditional decision-making mind frames. Likewise, the focus of this paper is not on the so called energy dilemma [37,38] and does not approach systems sustainability from the broader perspective of sustainability, widely discussed in the literature already [34–43,50–53], but rather from a different, more narrow and concise one. It does so by looking at concrete systemic and operational aspects of HMS and how to operate them towards achieving and maintaining efficient equilibrium state (homeostasis). The paper has four sections; the first and second offering an introduction to the subject, addressing the very nature of sustainability and SES characteristics, differentiating the authors view which supports the approach being presented here from the mainstream literature views. Also in section two the energy demand-side versus supply-side response management strategies are discussed in an effort to reconcile and combine strategies towards efficient equilibrium. Likewise, the general approach and methodology as well as the technology work scope are also presented in this section, along with the HC models and the various coordination and control criteria employed in the simulation phase. The third section presents the simulation results analysis of the different scenarios and strategies based on the predefined criteria as well as relevant considerations regarding the overall approach in light of the results. The fourth and final section offers final discussion and conclusions.

1.1. Sustainability and sustainable energy systems

Sustainability and sustainable energy systems (SES) are not the same. Yet often times these two terms are intertwined and used almost indistinctively in the literature. Sustainability is systemic in itself. It pertains to the definition given at the beginning of the paper, and may not necessarily be understood as the same thing when dealing with HMS. For SES to exist – particularly in the case of HMS connected to the grid without energy storage – the concept of 'built-in sustainability' in a system is of paramount importance and must be thoroughly understood. This goes right along with effective and productive energy supply and consumption management; one where energy efficiency and 'efficient equilibrium' (homeostasis) in energy intake and expenditure play a crucial role. Upon looking at HMS (a small PV-wind microgrid for example) connected to the grid, operating without energy storage, and supplying electricity to a group of residential consumers somewhere, this paper views such a system not so much as a sustainable socio-economic system but rather as a dynamically complex, adaptive socio-technical system where cybernetics [15] is a key factor. In such a case the interaction of consumers – whether these may be small industrial or residential or a mixture of both – with the grid-connected microgrid is vital in making this whole socio-technical system more efficient and sustainable over time [7–11]. Moreover, for the purpose of simulating the energy sustainability (ES) strategies being proposed here for HMS – taking real energy consumption data from an existing community in Chile – the paper looks at the particular case of a grid-connected microgrid without energy storage that is connected, through a parallel network, to a group of homes termed a sustainable block [8–11] in a rural location of Chile. The renewable microgrid's power supply to consumers may satisfy if not all at least a good portion of their electricity consumption needs (close to 80% in average for this small PV-wind hybrid energy system's configuration and design). However being the renewable electric power from HMS a scarce commodity, clean and inexpensive energy produced in limited supply, some prerequisites must apply in order for consumers to be eligible for such clean and inexpensive electricity that can substantially lower their monthly electric bill and carbon footprint. First it is proposed that in order to build a more flexible, diversified and sustainable electric power infrastructure [7], distributed generation (DG) systems in the form of grid-connected mini and micrograms must be implemented with multi-criteria decision making schemes for the management of microgrids power supply versus energy consumption behavior [54–56]. This energy solution calls for well defined supervisory control strategies for HMS based on certain predefined criteria – tailored to suit specific communities needs and to accommodate the existing EPS infrastructure conditions of the location – for the efficient management of energy supply and consumption [8,9]. Such strategy should seek to instill and condition a particular behavior on the part of consumers that makes the whole socio-technical system – a complex dynamic system in itself – more flexible, adaptive and energy sustainable as the system matures. For this it is essential to understand that new design, planning and control strategies ought to emerge [7–11] which may allow new, more innovative technical and operational visions to be discovered [57–64] for the successful integration of DG solutions to the grid, departing once and for all from the more traditional, main stream road. This is not only necessary but crucial if society is to reach sustainable renewable microgrids someday – particularly in rural and remote locations in South America where the electricity supply service is expensive and often unreliable – employing a sound sustainability philosophy as guiding framework. Nevertheless, an important point worth mentioning here with regard to these new design, planning and control strategies – such as the HC models and operational strategies for HMS presented here – is that they ignore the interrelationship between power generation and transmission systems, which may be an important assumption made going forward, as shown in several articles [65–73].

In fact the development of microgrids and the integration of NCRE bring an entirely new paradigm in energy supply and consumption of end-users altogether, it is indeed a game-changer and power utilities and industry experts know it quite well, especially if two-way communication and control systems are incorporated, such as the case with smart metering and flexible power supply schemes proposed by HC principles and technologies [1–6,7–10,81,82]. Along with this, it is required to build a strong social agreement among the microgrid's stakeholders [16–36,39–53]to align all parties involved. Hence, in order to operate effectively, HMS must be able to coordinate and utilize their limited resources to deal with uncertainty and complexity effectively, following certain strategic guidelines [7–11]. These socio-technical systems must be able to acknowledge the tensions between flexibility and stability forces operating within them, and manage them in a way that best reflects their strategic choices in order to effectively build energy sustainability in the system. The system of interest here is that which comprises every other system involved—in essence a meta-system [8,9]. In this particular approach, the meta-system is comprised of the grid-connected microgrid, the sustainable block of 15 homes and the

mains. Both flexibility and stability depend on what is termed the 'meta-controllability' of the socio-technical system, wherein it is the role of the supervisory control system to be implemented for the microgrid to determine when and how much renewable power is supplied, based on the particular energy consumption pattern exhibited by the consumer. For this a well defined HMS energy generation and supply strategy is defined which seeks to promote and instill efficient, thrifty energy consumption behavior in energy consumers. In order to be effective, such a strategy must be implemented through certain reward-based control criteria, employing the concept of homeostatic control. This ought to be linked to specific strategic needs and objectives of the meta-system based on the particular community and the resources available. Hence it is the system's designers and developers who are called upon to establish the right balance between stability and flexibility in the HMS coupled to a set of consumers and connected to the mains, understanding that both are desired properties or qualities of the socio-technical system. Such properties must be engineered in the system itself – built into it – not added onto as they do not oppose one another, contrary to what some might think. Both flexibility and stability complement each other in the HMS as perturbations and uncertainty may come at anytime as RES-based HMS are intermittent in their generation unless provided with adequate energy storage and/or with readily dispatchable power generation devices such as diesel engines. Such perturbations and uncertainty may come from within or from outside of the system, affecting the stability and flexibility of the system, its capacity, operability and objectives therein, thus testing its resilience and robustness [7–11,12].

1.2. *Renewable energy technologies (RET), the role of energy efficiency and equilibrium in hybrid micro-generation systems (HMS)*

Regarding energy production and supply as well as energy consumption behavior – and with regard to micro-generation power systems in particular – it is important to make the whole process as visible, uncomplicated and straight forward as possible [7–11] where users know enough about the system and what is required from them to make the HMS work optimally in terms of power supply and consumption. These ideas have already been brought up in various ways and discussed in depth by other authors, where adequate examples and alternative approaches are also shown [18–36,39–53]. In Chile, as in other countries, micro-generation will need to become more widespread and with it, the need to make these energy systems more environmentally friendly, sustainable and reliable. For this to come true it is important to device efficient and effective strategies for operating such microgrid systems, integrating them fully to the grid [7–11,57–64] whenever possible–a much more efficient option than looking to incorporate them as stand-alone energy systems. It is here where the concepts of EE and efficient equilibrium (homeostasis) come into play, just as flexibility and stability must both co-exist in the operation of EPS to make them more resilient and sustainable. They must be incorporated into the equation to make these systems more efficient and effective both technically and operationally. If design characteristics of EPS are built into the system with the concepts of EE and equilibrium in mind, the chances of making more sustainable EPS increases substantially [7–12,24–36,74–82]. These ideas will be discussed further next more in depth.

In order to be truly sustainable, living systems such as the microgrid supplying electricity to a group of homes analyzed here – indeed a highly complex socio-technical system in itself – must be efficient in their energy intake and expenditure just like living organisms in nature are. The more thrifty and efficient they are in their energy consumption, the more likely the system is to become sustainable in the long run, especially when power supply is not guaranteed on a continuous and reliable way [7]. For this to occur, the concept of thriftiness and efficient equilibrium (homeostasis) must be taken fully into account. A dynamic system may reach equilibrium yet not be efficient and sustainable; just like a fat person may reach an equilibrium condition in regards to his/her energy intake and expenditure, yet be far from healthy and efficient in his/her use of energy. Thus an energy efficient living system must reach a sustainable, efficient equilibrium state and always strive towards this–as part of its ES strategy. There is just no way around it, and it is here where cybernetics [13] comes into the picture along with HC. Both the feedback loop concept and HC principles come into play as valid benchmarks or touchstones upon which to guide designers so that energy users of the HMS connected to the grid can play – and should play as Schweppe and his team explicitly stated – a more active role in the efficient and sustainable energy supply and consumption management of the system [1–4,7–10].

The main problem which prevents a more widespread penetration of renewable energy technologies (RET) is the variability of the primary sources of energy, mainly sun irradiance and wind, with never a steady output for long periods. Therefore there is the need to complement each other and to add, whenever possible, a means of dispatchable energy storage system or a diesel engine to make the microgrid more readily dispatchable [7]. Several strategies have been studied for minimizing the uncertainty effects, each one having different trade-offs among costs, environmental impact and easiness of implementation [12–36,39–64,74–82]. Likewise there are technical resources that can be built into the system such as feedback [27–32], smart metering systems and other control technologies which provide the means to consumers in real time as a possible way to overcome intermittence of RES and achieve energy balance in a microgrid besides using diesel generators and the grid support. For example, there are in the market solar water heating systems as well as natural gas technologies for residential heating systems which have associated display units in their installations that show the water temperature and the amount of energy absorbed from the sun in a given period; or else the amount of natural gas that is being consumed and BTUs produced and at what price, depending on the time-of-day rate, respectively. Again, there are no norms as yet, especially in developing countries like Chile, but such displays do have a powerful effect in raising awareness in energy users on saving gas or electricity and keeping energy consumption low and thrifty. In reviewing [18–38] authors discuss the perspectives of RES and HMS, along with a battery of policies and regulations proposals for their implementation in different scenarios and geographical locations, in the making of strategies for a sustainable development. Such strategies typically involve three major technological challenges: energy savings on the demand side or demand side management [18,61–64,81,82], efficiency improvements in RET's energy production, where much fruitful work has been done already by many researchers and continues to be done on several fronts in order to improve microgrids operation and productiveness [18–36,39–53,57–64,74–79]. To these must be added the important role of energy efficiency and its impact on the general strategies being proposed here [7–10,27–33,39,43], along with the replacement of fossil fuels by various sources of renewable energy whenever possible [57]. This last one in particular represents a long standing challenge that continues to be an uphill battle to this day, especially in Chile, a country endowed with abundant RES yet having only 3% of its energy matrix comprised by NCRE. Consequently, large-scale renewable energy implementation plans must include strategies for integrating RES in innovatively designed energy systems, influenced by energy savings (thriftiness) and energy efficiency (EE) measures [7–10]. Denmark is a good example of this, where renewable energy systems have made great strides thus far. Authors in [49] make a convincing case,

concluding that sustainable energy systems (SES) based on RES are possible. However, when discussing flexible technologies to increase energy savings, applying EE measures and deepening renewables penetration, the problem of systems integration becomes important and must be taken into account in designing new strategies to be implemented therein [42–48].

In reviewing [20–26,33–36,74–79] authors present the current state-of-the-art in microgrids addressing technical, operational and environmental aspects along with several local and regional issues to consider, as well as the barriers that are being encountered for their integration to the grid. They assert that expectations of the microgrid performance is high, therefore issues related to their standards, autonomous operation, control strategies, regulatory barriers as well as their protection and islanding operation are all discussed therein, along with other important aspects of such DG systems. However, upon careful analysis of these and other pieces of literature, one sees much of the same issues being addressed and discussed offering different technological alternatives, viewpoints and integration options; yet nothing is said in regards to possible means and ways of turning microgrids into SES. They point out that one of the technical challenges that microgrids face lies in the availability of low-cost technologies for their safe and reliable operation, emphasizing the socioeconomic, regulatory and environmental aspect as so many others have done. They also discuss the microgrid's ownership issue as well as regulatory policies at length, both important hindering factors in the proliferation of these systems [79] according to these authors. On the other hand, in [18] authors outline the design considerations needed to produce SES for night-time lighting of footpaths emphasizing the need for a combination of different RES which has the advantage of greater balance and stability, where winds are usually stronger in winter and during nighttime, and solar irradiation is higher in summer and during daylight. A balanced system provides stable outputs from sources such as these and minimizes the dependence on variable output upon seasonal changes [19], again a fact that although is true and quite relevant, nevertheless it has been overemphasized at length already in the literature. However, no precise or in-depth analysis is offered on how systemic, technical and operational aspects of such systems can contribute to making them more sustainable and resilient other than suggesting that the use of different RES may bring a more economically feasible and efficient HMS, given that renewable energy on a small scale is still a relatively expensive option compared to conventional energy use [19]. Moreover, authors in [19] add that due to the present costs of implementing RET solutions – particularly microgrids – to gradually replace traditional energy sources, in order to meet the increasing energy demand, it is still not cost effective compared to the use of conventional fossil fuel-based energy sources [19], something that to this day is still shared by many industry professionals, who still look at HMS with disdain when comparing RET with conventional technologies. So it is the case, they argue, where electricity is supplied by the electrical distribution network [19,20–26]. However, they fail to notice one important fact that needs to be fully accounted for: aside from the fact that non-conventional renewable energies (NCRE) have a strong environmental appeal all over the world today, and Chile being no exception, there is also the existence of dispersed population settlements everywhere with sometimes very expensive grid-supplied electricity that is often poor in quality and reliability, and where livelihood is very dependent on local economic factors of production. Latin America in general and Chile in particular – a country which is rich in RES and where environmental concerns are a main issue of discussion today and will continue to be over the next decades with greater societal strength and impetus, yet whose price of electricity is the highest in the whole region – have large numbers of rural settlements, mainly small-size communities scattered everywhere that must pay a high price for electricity supplied by the utility grid or by other fossil-fuel based energy sources. The reason for this – in addition to the fact that there is a very concentrated electricity sector, both at the generation and distribution level, with a very small number of players offering services – is the transport of electricity and fuel over very long distances, with a difficult geography and territorial permits, which contributes significantly to the problem of high cost of electricity. Therefore, on top of what has been discussed so far regarding energy and energy systems sustainability, this fact brings an additional argument in favor of building more adaptive, flexible and resilient SES [7–10,12,13,80] employing new and innovative strategies to augment their responsiveness, that are technically and operationally sound and economically feasible [7–10,19–36].

2. Sustainable energy systems characteristics

An open system is one in which there exist an exchange of material, energy or information between the system and its environment. By its very nature, a HMS is open because the inputs include the effects of the environment [19]; yet if analyzed systemically one realizes that both inputs and outputs affect the system and its environment. The inputs of an open-loop system are independent of its outputs, which are not linked to its performance; therefore such a system cannot regulate itself. On the other hand, in a closed-loop system where a feedback function is provided, the outputs have influence on the inputs, and feedback is generally used for control. As a result the system can control itself and be sustainable [7–10,19–26]. Although HMS are open, they can be thought of and have the characteristics of a closed system if feedback is implemented in such systems for monitoring systems health and performance, as well as the behavior of consumers (loads) who are part of the system itself (thus a sociotechnical system), along with the power supply from the HMS as the input regulated and monitored by the supervisory control system [7–10]. However, both supply and consumption of electrical energy are quite dynamic and continuously changing in HMS, so there must be a strategy in place for varying loads behavior and a changing power supply from such HMS to make it more efficient and sustainable from a systemic, technical and operational standpoint. With a backup system as another energy source such as the utility grid (a slack-bus), a stand-alone diesel plant or a rapidly dispatchable energy storage system (energy buffer) such as a battery bank, the system can be designed as a partially closed-loop feedback system [7–10,13]. Next in Fig. 1 there is a schematic diagram which illustrates how the homeostatic regulation (HR) index works. The HR and adaptive control mechanisms are embedded in the supervisory control system of the microgrid. These are control algorithms that may be programmed in the system and may be customized according to the characteristics and necessities of the target community.

2.1. Energy demand-side versus supply-side response management strategies: An effort to reconcile and combine strategies

Key to making micro-generation systems sustainable, especially those connected to the grid, is their capacity to maximize energy production and supply under changing conditions and circumstances, coupled with some form of energy balance or efficient equilibrium (homeostasis) linked to thriftiness, EE and energy sustainability strategy. The key point to be made here is the need to elicit both in the energy demand and consumption of those having access to HMS supply, making such traits a habit that can ensure system sustainability [31]. In regards to this, Lotka [80] said: "Systems prevail that develop designs that maximize the flow of useful

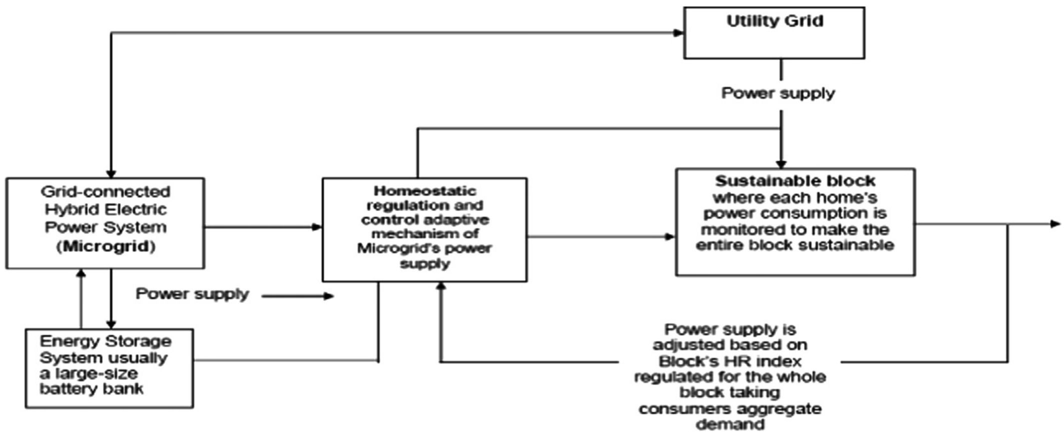

Fig. 1. Diagram of homeostatic regulation (HR) index function with dynamic system regulation for a grid-connected microgrid, in this particular case, with energy storage.

energy". Most of the literature on the subject addresses energy demand-response management in one way or another and authors respective views are elaborated and discussed therein. It is true that loads can participate in energy demand-side management strategies [18,61–64,81,82], especially in small-size communities interacting with the local utility grid or with other microgrids operators through smart metering systems for example. Thus, when there is sufficient installed capacity, the microgrid can export power to the utility grid or exchange with other microgrids if a cluster of these were installed somewhere and appropriate control and communications connections were available [19,23,25,26]. For a renewable microgrid installed in a rural, small-size community of which there are hundreds in Chile alone, and many thousands in South America, loads are no longer passive elements like in the big city or in other typical urban settings, but very dynamic and different, and as such should play a role in the grid-tie HMS's energy management as well [7–11]. Thus customers and their respective loads can participate through their energy consumption habits and practices in demand response management and load shedding strategies as opposed to just being passive spectators, even if they do not directly intervene in load shedding [44]. Therefore the power supply control management strategy to be implemented must consider this issue as well, especially in rural, remote or isolated communities where it is difficult to attain power balance due to various limitations. It is here that load control strategies can play a critical role, especially in places where electricity is expensive and/or where sometimes a faulty or inadequate electric power supply exist, since these have the potential of significantly reducing the energy price, installation costs on additional units serving loads in peak intervals [49]. However, these strategies need to ensure that critical loads in the microgrid receive enough energy whenever and wherever it is needed. An example of such critical loads would be health care facilities, public transport that operates on electricity and schools [7]. Additional strategies include customer service differentiation, power quality and reliability enhancement of specific loads [48,49]. Again, particular interest is placed here on grid-connected microgrids without energy storage which have the main grid as backup and may eventually employ energy storage systems (ESS) such as a battery bank if no environmental and regulatory restrictions are in place. Although such microgrids operate connected to the grid with which they synchronize fully by means of an inverter (whether it may be a bi-directional or a unidirectional one), they can also, if necessary, operate autonomously, as a stand-alone plant at certain times of the day or when a scheduled maintenance is being performed at main grid equipment [42,43].

Traditional EPS planning and design approaches consist mainly of forecasting energy demand over specific periods based on historical data, accounting for seasonality and other relevant factors, and adjusting the plant's equipment to fit the supply-side based on these projections. Others focus chiefly on social, regulatory and environmental issues. Such approaches completely ignore the possibilities that energy conservation linked to thriftiness and EE in energy consumption may offer and what their impact on energy sustainability might be through the control of energy supply and demand in terms of quantity and quality [7–10,31,33–38]. In the case of demand response management strategies, instead of matching the limited energy supply to the consumers needs, the consumers demand (loads) is adapted to the available electrical energy supply capacity of the plant, without compromising any critical activities performed by particular users such as hospitals and schools [7,18,37,38,41,61–64]. Thus energy supply can be controlled by means of a supervisory control system like SCADA, based on set points and load range limits limiting the amount of power and also the quality, offering differentiated power quality levels adapted to the consumers needs, or by limiting the amount of energy flowing to the customer at certain times of the day, for example, by offering different electric power supply service levels and rates to different customers [7,37,38,41] especially when there are residential customers mixed with commercial ones, all together in a particular location, as it is often the case in urban and rural areas of Chile. These ideas although sound and effective are not new and have been put forward many times before although not taken far enough. Yet what is new and innovative here is the idea of reconciling and combining demand response management and reward-based strategies for supplying renewable power (RP) to a group of residential consumers somewhere. Therefore the paper seeks to show that this is not only possible but necessary for building truly SES, and it can be done applying a reward-based system such as the one being proposed here where the rule of merit operates. This in order to elicit thrifty, efficient and well-balanced electricity consumption (with auto-load shedding if you will, where customers curtail their own demand for energy in return for cheap RP supply) to achieve a more SES [8–10].

Power supply differentiation could have in theory various levels, but the most basic ones are between high consumers and low, thrifty consumers with a segment in between. This is somewhat similar to the demand-side or load management strategy proposed by some authors [6,18–22,24–26] for utilities and mini-grid power supply. In such cases a distinction is made between sensitive (such as healthcare facilities, communal service buildings, communication infrastructure and others), where a steady, good quality, uninterrupted power flow is necessary on a 24-h period, and non-sensitive loads which may be deemed more controllable and offer greater degree of slack for load shedding and variations in the quantity and quality of power being supplied

throughout the day [6,18,19, 33–36,41,42]. Likewise, these different terms of service can be defined in service contracts between particular consumers and local minigrid operators with EE incentives [18,36,39,41–43]. The combined application of energy demand response management as well as power supply control management strategies may seem like an appealing and sensible solution for building more efficient and sustainable energy systems but, nonetheless, it is a complex and delicate endeavor that must be handled with caution; not before having researched thoroughly the consumers profile and characteristics of the target community for they require a strong social agreement among the microgrids stakeholders [18,36,39,41–43][61–64]. Thus, before implementing such strategies, it is fundamental for the project's management to evaluate the willingness, ideas and attitudes toward renewable power supply, EE and energy sustainability, as well as the degree of sensitivity of the various stakeholders with regard to the initiative in the community where the implementation is to take place [7–11]. This is particularly important in ensuring that the system's design and planning are adequate, taking into account the various factors with the objective of having a successful outcome. Likewise, part of the planning stage must consider a thorough evaluation of the population and its characteristics as stated previously, where strengths and weaknesses are identified along with opportunities and threats for the feasibility and success of the initiative. Thus, depending on the results of the analysis carried out, there must be a set of appropriate measures to be taken to deal with these findings before the implementation of the strategies are in place [9]. An important part of such measures to handle inadequacies and/or inconsistencies between the community and the implementation design and planning include public relation (PR) campaigns, various training programs, social and economic incentives for the people and other methods [18,36,39,41–43,61–64]. Nevertheless it must be an action point first and foremost in the project's agenda to assess the willingness of individuals to change their habits, reducing their energy consumption patterns linked to a change of lifestyle, something which is very difficult to achieve. These strategies must also employ the right technology and operational framework capable of regulating and controlling these energy consumption patterns and inducing change in consumers based on some kind of reward mechanism. This is being done nowadays in one way or another to various extents by the introduction of the smart-grid concept and their related communications and control infrastructure. However these strategies must also be supported by the right policies and regulations as seen in the literature.

2.2. Homeostatic control in electric power systems (EPS) supply

Although the literature in homeostatic control (HC) has been pretty much confined almost entirely to the biological and medical sciences circles over the decades, there was an exemption to the rule as there always is. This came from Schweppe and his group of collaborators at MIT back in 1979 and early 1980s [1–6]. They were truly visionaries of the changes that were to come, especially back in those days when reality of just about every aspect of the industry was much different than it is today. They were the first to introduce the term HC in regards to utility power systems supply management aiming for more flexibility and adaptability being built into the system at the time, based on customer demand-response management. The essence of their approach to HC for electric power utilities was based on the utility-customer interaction through real-time communications [1–6] and how this recursive and continuous interaction and interdependence between the power utilities and their customers could change the marketplace of EPS for the better. At the time it was not clear which way was power systems control going to go, yet there was a general consensus among academics and industry experts that a more flexible, distributed adaptive control approach, with more customer input, would suit the industry better and would best exploit the capabilities of emerging new technologies in communications and digital signal processing of the times [5,6]. Homeostatic utility control, as described by Schweppe et al. [1,2,4] and emphasized by Sterling et al. [3] and Tabors et al. [6] is "an overall concept which tries to maintain an internal equilibrium between supply and demand" and, as stated by the authors: it seeks to do this by informing the customer of the time-varying prices of electricity, whereby the customer can make his/her own decision independently, as opposed to having conditions being imposed to him/her [1–6]. Something that normally happens even to this day with residential customers and with small and medium-size commercial and industrial enterprises. According to Schweppe et al. "It is to the advantage of both the customer and the utility that the electric power system be planned and operated as economically and physically efficiently as possible subject to constraints on environmental quality and on system integrity" [1]. Of course, back in those days they envisioned this approach especially for large industrial and commercial customers who in general have very different types of loads at different times of the day. Sometimes they need large instantaneous amounts of power supply for short periods, for example for high-power intensive industrial processes like iron melting and at other times they only need smooth, steady energy flow such as space heating. Thus it is possible to coordinate and control electricity supply in a manner that differentiates between these two types of energy needs and device a solution to reschedule power supply priorities based on this as they did. On the other hand, commercial and industrial customers have traditionally enjoyed much more flexibility and a higher degree of recourse/leverage with utilities in general, especially with power utilities than small customers do, and where residential customers in particular have enjoyed none. Back in those days the power generation and distribution industry was extremely centralized and particularly powerful given the fact that the rise of green, distributed electric power systems supply with the boom in NCRE was not yet forthcoming. All this, as well as EE, mini and microgrids' power generation and a whole array of new distributed generation technologies [19–26] that came into existence in the 1990s were still in infancy or in embryonary state at best back then. Along the same line, [81;82] are both based on the same principles and ideas initially put forward by Schweppe and his group, but this time focusing rather on the smart microgrid which is injecting power to the utility grid, and analyzing the issue of HC from a customer demand-response management as Schweppe and his followers did back then. In Ramchurn et al. [81] authors present a new control mechanism to model and control a hybrid renewable energy system in microgrid configuration injecting power to the grid and also supplying power to a number of individual homes, each having a battery bank or similar energy storage device, yet the high cost of ESS in general and the cost that such residential energy storage devices would have, along with other considerations such as leakage, maintenance and disposal of these make this approach rather unfeasible for the time being.

Based on what has been discussed so far one may envisage small communities in different locations that are better able to become energy efficient and more sustainable in terms of their electricity consumption than others, deriving economic benefits from this as a whole [7–11]. Hopefully this will somehow lead to a trend in new, more adaptive, thrifty and sustainable HMS for rural communities worldwide someday, where DG initiatives employing diverse RET in the form of flexible microgrids can integrate with the current utility grid infrastructure without having the need for energy storage means every time, thus allowing a new hybrid, more sustainable power infrastructure to evolve and grow. Next

in Fig. 2 there is a possible microgrid's configuration option for implementation in a rural or remote community. In this case a battery bank (energy buffer) is considered for a grid-connected microgrid.

2.3. General approach and methodology

Three distinct scenarios were established in terms of the energy consumption demand data to be used for the simulation phase. First there is a base case scenario, where a homogenous set of demand data was established using the values of the energy demanded by a small community, quite representative of the type of rural communities this work is especially focused on. The values corresponded to 12 months worth of data which were then averaged and thus a new set of data was produced by varying these new averaged values over a certain range of variation, based on the original values of the target community. The data gathered corresponded to a particular rural community of Chile. This set of data was then randomized to produce a different set of values for what became Evaluation (1) and (2) stages of the simulation phase. This average or medium case scenario is used as the base case upon which to make a comparison with the other two cases studied, producing a range of variations in the data to enhance and make more realistic the simulation efforts. The two remaining cases already mentioned are the high-difference case (2) and the low-difference case (1) where the difference between the two has to do with how wide of a difference there is in data values from the base case values in the electricity demand of consumers. Such consumers are then to represent a cross section of 15 homes – a sustainable block – in a hypothetical community. The low difference case (1) has small difference range values from the base case and represents a scenario of a very homogenous power consumption, quite common in some small communities, whereas the high difference case (2) is very heterogeneous, as there are larger differences in data values for the electricity consumption of the 15 homes, thus representing another type of power consumption with more heterogeneous habits as observed in other communities. Likewise the hybrid energy system (HES) was simulated extensively on a separate basis and a substantial set of values (Potencia_HES) was produced from this which presented a realistic power supply variability as a product of randomization. This allowed simulating the continuous renewable electric power generation of the microgrid, producing a set of randomized values of the power generation of the HES over a continuous time frame which lasts a complete 1-year cycle ($\Delta t = 1$ h, where $t = 8760$ h in 1 year). Therefore, simulation was done based on the three distinct scenarios for the simulation phase, namely a base case; a low-difference (1) data range case (representing a very homogenous energy consumption of the entire block); and a high-difference (2) data range case (with very heterogeneous energy consumption for the entire block) in terms of the power supplied vs. the energy demanded by the 15 homes during a complete 1-year cycle.

Finally a set of merit-based HC strategies is introduced for the coordination and control of such systems based on five distinct criteria devised to enhance homeostatic regulation and control, assigning renewable electric power supply from the microgrid to the homes in the sustainable block. Based on the criteria utilized for experimentation purposes, renewable power is supplied only to those homes which comply with the set criterion in an effort to influence and condition the block's electricity consumption in a way that ensures that the meta-system is sufficiently efficient and sustainable (has a higher exergy content) overtime. Thus each of the three scenarios already described is analyzed with regard to each particular criterion employed, for the purpose of deciding whether or not the control and coordination strategy (built into the microgrid's control system) will assign renewable electric power supply to the homes in the sustainable block. These eligibility criteria are based on specific conditions inherent to each criterion being exercised by the supervisory control system on the consumers to which the microgrid provides service. These conditions were analyzed and elaborated therein for the purpose of potentially implementing them in the control system of a microgrid supplying a particular small community somewhere. The rationale behind this is explained by virtue of the fact that the renewable power (RP) being generated by the microgrid is a scarce and limited commodity, and therefore it must be managed and utilized efficiently and thriftily. The question then of whether a particular house within the sustainable block is eligible or not to receive inexpensive RP supply from the HMS will depend strictly on merit. That is, it will merit eligibility for RP supply access only if

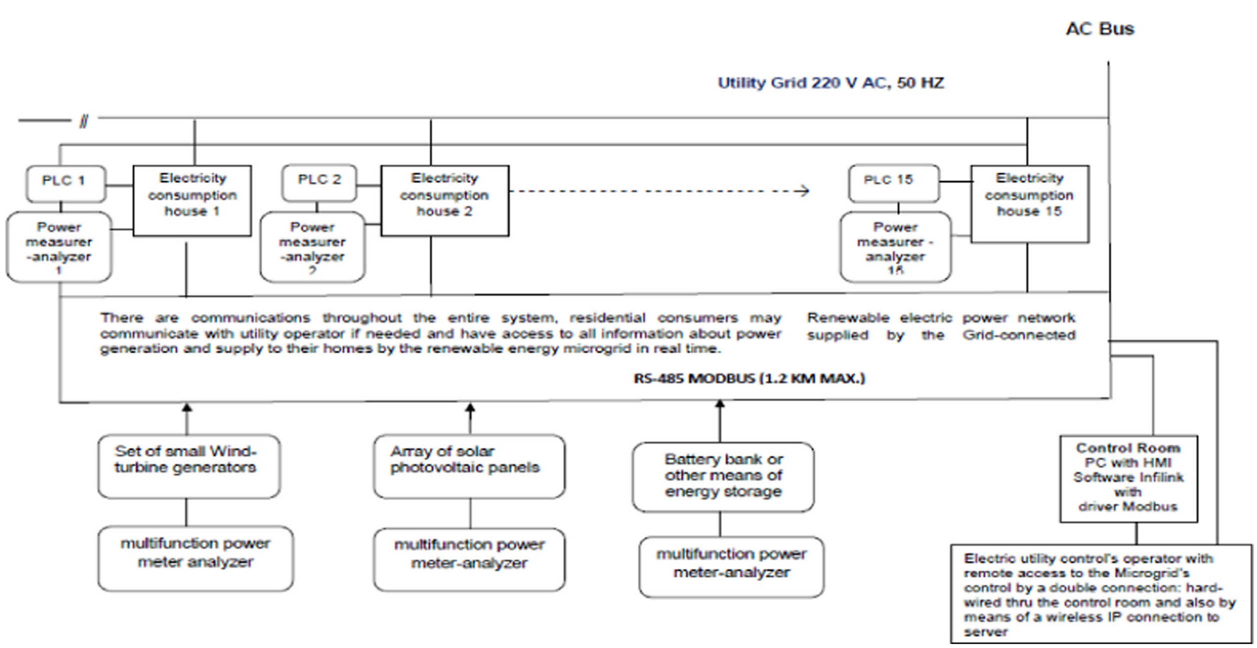

Fig. 2. Diagram showing a possible system's configuration for implementation of the homeostatic regulation and control strategy to coordinate and control a grid-connected microgrid in this particular example with an energy storage system.

the particular home's energy consumption falls within a certain predefined range considered thrifty, efficient and energy sustainable in terms of the entire block's demand – therefore the term sustainable block – which will allow for and contribute to the ES of the community as a collective. This may change however upon considering the energy consumption characteristics and living habits of a particular community's energy needs. Thus the microgrid's supervisory control system will assign power supply to the home therein albeit with a limit (ceiling) based on the needs of the entire block. Otherwise, it will have to continue consuming electric power from the utility grid at much higher prices.

Thus this particular HC approach to micro-generation systems aims to analyze the grid-connected microgrid in terms of its built-in ES capabilities, yet being analyzed from the power generation and supply standpoint. Here the systems involved emulate the behavior of dynamically complex adaptive systems (CAS), common to all living organisms which employ homeostasis regulation and sophisticated adaptation mechanisms to face the challenges that are brought upon them in an effective and efficient manner in order to reach a sustainable, steady-state energy solution for the entire system. This is especially important when it comes to difficulties and adverse conditions being imposed on such systems by changing environmental conditions and other circumstances that challenge their adequate operation and sustainability. As a result of the above it is possible and eventually desirable, in order to build sustainable energy systems' strategies – especially at the micro and mini-generation level – to influence and condition the electricity consumption of users when renewable electric power supply is scarce and randomly changing, as it always is with microgrids. This ought to be done in a way that makes the intervening systems operation more efficient and allow for a sustainable energy strategy to emerge as a result of the continuous interaction and co-evolution of the CAS involved: the 15 homes which form the sustainable block, the grid-connected microgrid and the mains. Hence, under a controlled set of conditions for the sake of simulation efforts regarding the microgrid power supply which is coupled to the main grid by means of a grid-interactive inverter, and connected through a parallel network to a sustainable block, consumers may satisfy if not all at least a good portion (close to 80% on average) of their electricity consumption needs, enough to substantially lower their energy bill. This continuous interaction among the three systems (the meta-system) and their eventual capacity to work out a sustainable energy solution to the energy needs of the entire block is the core of the approach presented here.

2.4. Technology work scope

Here the focus is on renewable power (RP) supply to small-size communities, which are abundant in Latin America and in Chile in particular. A specific residential arrangement consisting of a group of homes in a rural area of Chile is selected. This arrangement, termed a sustainable block [9], is coupled via a parallel network with a solar PV-wind grid-connected HMS (a renewable microgrid) operating without energy storage. From this DG solution consumers may satisfy if not 100% at least 80% of their electricity consumption needs on average. Here the utility grid, to which the homes are also connected, acts as the back-up system (slack bus) and is always ready to provide more power if necessary. Likewise, the key enablers in this complex socio-technical system are communications and control signals built into the supervisory control system and a communications network that includes smart metering in every home and connects the utility grid's control operator with the microgrid and with energy consumers in their homes. The three systems comprise an interconnected meta-system [9]. Signals are sent upon reaching a certain set-point to the different components which comprise the entire system. The approach presented here seeks to control the RP supply to the homes by means of particular merit criteria which reward thrifty, efficient energy consumption of electricity supplied by the HMS in order to avoid having to purchase too much power from the mains. Here there are behavioral adaptation mechanisms at play as a means to exert control over certain parameters in hybrid micro-generation systems. Hence RP is supplied only to those homes which comply with specific energy sustainability (ES) criteria in an effort to condition the block's electricity consumption through HC system strategies in a way that ensures that the meta-system is sufficiently efficient and sustainable overtime. Simulation carried out provides a good fit to the data utilized over several rounds of data, and the response of the system to changing power supply under different scenarios was characterized by its consistency and logical framework supporting the model employed. Furthermore, results show how important homeostasis regulation is in ensuring a successful collective effort from both individuals and community as a whole toward ensuring the system's overall sustainability. Below is the general nomenclature utilized for the code programming and the five different criteria employed for the supervisory control strategies, beginning with Criterion 0 and ending with Criterion 4. Each represents a possible strategic alternative for a HC model to be implemented in the microgrid through its supervisory control. Each criterion is depicted by its corresponding flow diagram yet some minor omissions are done for the sake of brevity.

2.5. Nomenclature

i	home
t	time (h)
m	month (m)
P_{HES_t}	power generated by HES at time t (kW)
d_{it}	power consumption of the home i at time t (kW h)
D_t	sustainable block power consumption at time t (kW h)
$P_{home_{it}}$	power bought from grid for home i at time t (kW)
$\bar{t}_m$	average time for house i having to purchase power (how much time in average was power purchased from main grid)
$\bar{t}_{m-1}$	.
$\bar{P}_{im}$	average power purchased for house i in the month
$C_{i_{SB}}$	cost for the whole sustainable block

N denotes the set of homes which comply with the set criterion.
Note: 1-year simulation cycle.
$\Delta t = 1$ h, where $t = 8760$ h in 1 year.

Criteria 0, 1, 2, 3 and 4 are shown next in order of appearance from zero to four.

2.6. Experimentation phase: Simulation of different criteria for assigning limited supply of renewable power to homes, addressing different scenarios and conditions with a grid-connected microgrid

In the experimentation phase simulation on Matlab 2010 was used to test the different criteria for assigning limited supply of renewable power to the homes in the sustainable block, addressing different scenarios and conditions with a grid-connected microgrid. Working with a grid-tie microgrid which is operating without energy storage is of course more difficult yet it may seem more appealing from the HC analysis viewpoint because upon extensive review of the literature one finds that it has not been

sufficiently explored, especially when it comes to issues regarding micro-generation systems integration to the mains, favoring rather the study of hybrid EPS that are comprised of various energy storage configurations and sizes [9,10]. Different demand and supply scenarios were analyzed in which the grid-connected HES may operate, employing a set of predefined criteria to be applied for RP control under these scenarios, and then evaluate the results in each case to draw some conclusions. The work carried out seeks to analyze the interaction between the electric utility grid (as a more complex, higher-order system) and the HES (lower-order system) which is coupled to the sustainable block, operating as a renewable PV-wind microgrid, able to generate about 80% of the block's energy demand daily. In light of this a demand curtailment is needed to reduce consumption in order to bring down to a minimum the amount of electric power drawn from the mains due to its high price. Likewise, possible coordination and control strategies are sought but from the power generation and supply standpoint rather than from the demand side management (DSM) viewpoint only, as this last one is treated in the microgrid literature at large. These strategies – which in this particular case take the form of a set of different power supply control criteria to be described later – are believed to play an important role in aiding and enhancing such recursive interaction in grid-connected HMS, coupled to a sustainable block [9,10].

Recursive interaction is common to all complex adaptive systems interacting among themselves and with their setting, as do all living organisms; particularly so when working in a changing environment, under a different and uncertain set of conditions, towards an adaptive, sustainable energy solution for the systems at play through emergence and co-evolution. In this example the HES is expected to operate in tandem with the utility grid and in island mode as a stand-alone power plant when the utility grid is down due to a power outage as a result of system fault or maintenance. Thus especial interest is placed on systems interaction, efficient supply and consumption of electricity and above all, ES for such systems. Hence, in order to instrumentalize the strategies before mentioned, there were five different criteria tested in three distinct scenarios which were designed for the grid-tie microgrid's simulation and experimentation phase. The microgrid was configured as a small PV-wind HES connected to the grid, operating without batteries due to local restrictions and regulations regarding chemical pollution from such energy storage devices at the location for which this DG solution is intended. For this a full and thorough evaluation of different systems configuration and optimal component sizing was done using freely available HOMER software to arrive at an optimum in terms of the hybrid renewable energy system comprising a grid-connected microgrid. This was done based on wind and solar power availability and plant capacity parameters for a specific remote location in Chile with a small population, typical of such small-size communities in Chile and South America (see Fig. 3 in [9,10]).

Below is Fig. 3 which shows a specific design of a control diagram for a piece of supervisory control logic to be implemented in a grid-connected solar PV-Wind HRES this time energy storage. The diagram illustrates how the microgrid's power supply may be controlled in parallel with the grid's supply and with the energy buffer (battery bank) to supply the single phase AC loads (the homes) in a sustainable block.

2.7. The three distinct scenarios for the simulation of the set of control criteria based on thrifty, sustainable energy consumption behavior

First of all, three distinct scenarios were established in terms of the energy consumption demand data to be used for the simulation phase. First there is a base case scenario, where a homogenous set of demand data was established using the average value of the energy demanded by each of the 15 homes corresponding to a particular rural community of Chile. This set of data was then varied to produce different set of values for what became Evaluation 1 and 2 stages of the simulation phase. This average or medium case scenario is used as the base case upon which to make a comparison with the other two cases studied, producing a range of variations in the data to enhance and make more realistic the simulation efforts. Then there are the two remaining cases, the high-difference case (2) and the low-difference case (1) where the difference between the two has to do with how wide of a difference there is in data values from the base case values in the electricity demand data of consumers for the 15 homes in the block. The low difference case (1) has small difference range values from the base case and it represents a scenario of a very homogenous power consumption quite common in some small communities, whereas the high difference case (2) is very heterogeneous as there are larger differences in data values for the power consumption of the 15 homes, representing other, more heterogeneous communities. Likewise the hybrid energy system (HES) was simulated extensively on a separate basis and a substantial set of values (Potencia_HES) was produced from this which allows simulating the continuous renewable electric power generation of the microgrid. Thus a complete set of values for power generation of the HES over a continuous time frame was utilized which lasts a complete 1-year cycle ($\Delta t = 1$ h, where $t = 8760$ h in 1 year). Therefore, simulation was done based on the three distinct scenarios for the simulation phase, namely a base case; a low-difference data range case (very homogenous consumption for the whole block); and a high-difference data range case (very heterogeneous energy consumption for the whole block) for the power supplied and the energy demanded by the 15 homes during a complete 1-year cycle. Likewise each scenario is analyzed with regard to each particular criterion that will be employed for the purpose of deciding whether or not the control and coordination strategy, built into the microgrid's control system, will assign renewable electric power supply to the homes in the sustainable block. These eligibility criteria are based on specific conditions being exercised by the supervisory control system upon the consumers to which the microgrid provides service. These conditions were analyzed and elaborated therein to be implemented in the control system for a microgrid supplying a particular small community by virtue of the fact that the renewable power (RP) being generated by the microgrid is a scarce and limited commodity and therefore it must be used efficiently. In addition to the latter, and for this particular case, it was chosen a HES configuration where there is no energy storage available as a back-up system, only the utility grid which provides unlimited yet expensive power supply. The question then of whether a particular house within the sustainable block is eligible or not to receive inexpensive RP supply from the HES will depend strictly on merit. That is, it will merit eligibility for RP supply only if the particular home's energy consumption falls within a certain predefined range considered thrifty, efficient and energy sustainable for the entire block – therefore the term sustainable block [9] – which allows for and contributes to the ES of the community as a collective, considering the characteristics of its energy needs and living habits. Thus the supervisory control system of the microgrid will assign the power supply to the home therein. Otherwise, it will have to continue consuming electric power from the utility grid at much higher price.

Thus this particular HC approach to micro-generation systems aims to analyze the grid-connected microgrid in terms of its built-in ES capabilities, yet being analyzed from the power generation and supply standpoint. Here the systems involved, which comprise the meta-system [8,9] already mentioned, emulate the behavior of complex adaptive systems(CAS), common to all living organisms

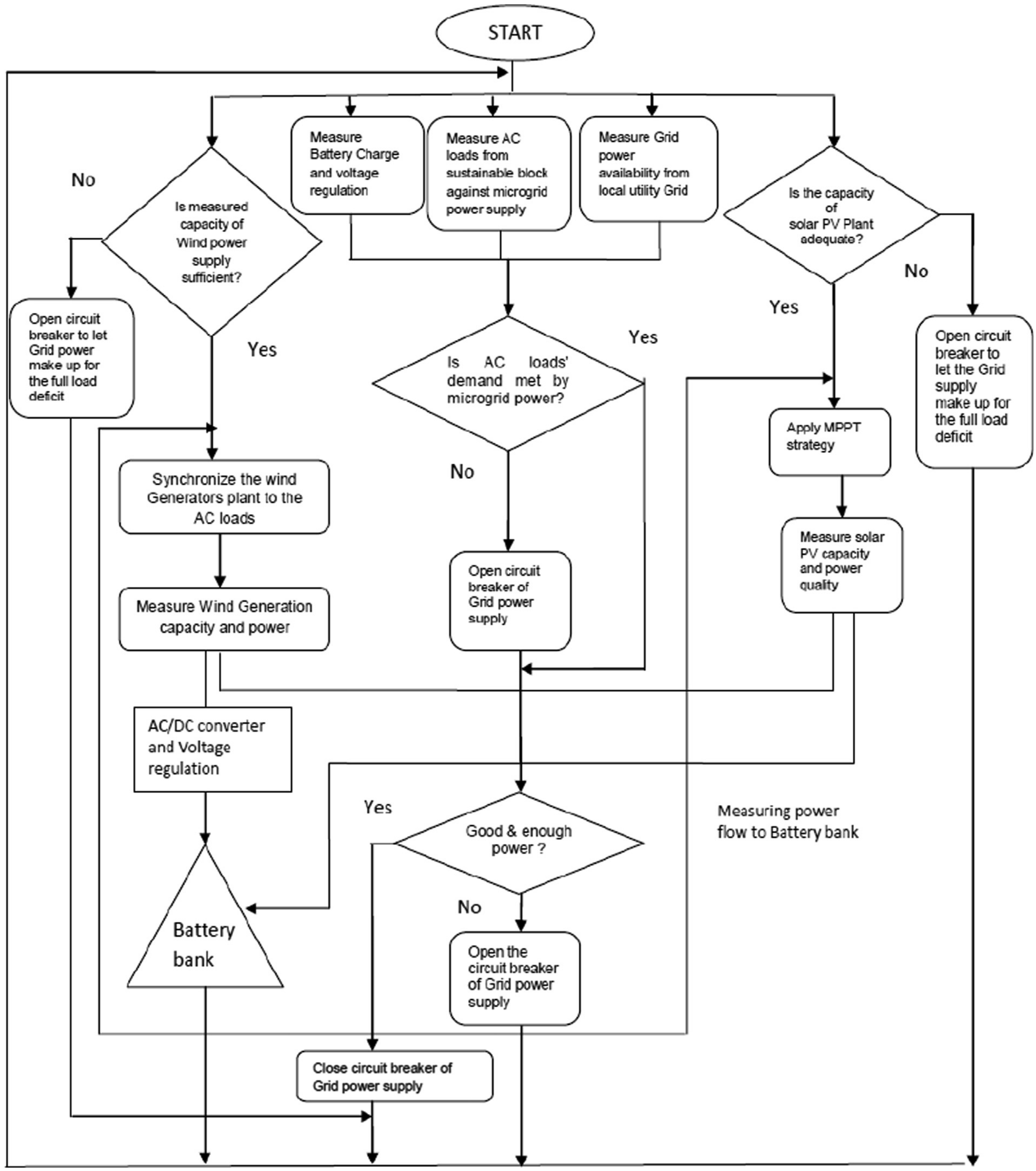

Fig. 3. Flow diagram of coordination and control system strategy for a grid-connected solar PV-wind hybrid energy system with energy storage.

which employ homeostasis regulation (HR) and sophisticated adaptation mechanisms to face the challenges that are brought upon them effectively and efficiently in order to reach a sustainable, steady-state energy solution for the entire system. This is especially important when it comes to difficulties and adverse conditions being imposed on them by changing environmental conditions and other circumstances that challenge their adequate operation and sustainability. As a result it is possible and eventually desirable, in order to build SES strategies – especially at the micro and mini-generation level – to influence and condition the electricity consumption of users when renewable electric power supply is scarce and randomly changing as it always is with microgrids. This ought to be done in a way that makes the intervening systems operation more efficient and allow for a sustainable energy strategy to emerge as a result of the continuous interaction and co-evolution of CAS involved: the 15 homes which form the sustainable block, the grid-connected microgrid and the main grid. Hence, under a controlled set of conditions (for the sake of effective simulation efforts) regarding the microgrid power supply which is coupled to the main grid by means of a grid-interactive inverter, and connected through a parallel network to a sustainable block, consumers may satisfy if not all at least a good portion of their electricity consumption needs, enough to substantially lower their energy bill on average. This continuous interaction among the three systems and their eventual capacity to work out a sustainable energy solution to the energy needs of

the entire block as CAS is the core of the research analysis and results presented here.

2.8. The different criteria used for the simulation phase and results in each case

There were five different criteria used for the simulation phase. These are described next, with each of their corresponding flow diagrams shown which depict the logic applied in each case. First the notation used in the set of criteria is presented. Each of the 5 criteria employed for the simulation phase uses the same inputs but with different control logic altogether. We use the power supply from the HES, which has been calculated for a PV-wind 30 kW small-size capacity microgrid, simulated for a continuous period of 8760 h (1 year) and duly randomized therein to simulate, as best as possible, the random variation in renewable power supply of a microgrid of this size and configuration. Another input is the grid's power supply which is considered a slack bus, being always available for electricity supply as a back-up system. Finally the electricity consumption of the 15 homes in the sustainable block is also simulated and randomized accordingly for the exact same period, 8760 h, but in addition to the latter, a variation in the range of consumption is introduced herein, which reflects three very distinct electricity consumption patterns. First there is the base-case scenario, where a complete sample of real electricity consumption data was gathered. The electricity consumption data obtained represents the consumption profile of a small remote community in Chile typical of the type of communities that this study focuses on to potentially introduce this technology eventually. The data was constructed averaging the values of the entire consumption period (several months) and then the data were duly randomized producing variations among the different values that best reflected a realistic consumption scenario of such community. Such randomization was done by means of an algorithm especially designed for this purpose. Then there is a more homogeneous consumption data, Evaluation 1, where values are closer together with less difference between each of the homes electricity consumption. Finally there is also a high difference scenario, Evaluation 2, with a much more heterogeneous consumption among homes. Next there is Fig. 4 right below which illustrates criterion 0; this is a very simple criterion where the electricity demand of the entire block is added up and then compared to what the HES is producing at any point in time.

Here the controller reads the incoming data values, power from the HES and each home's energy demand. Then it calculates the total energy demanded by the entire block, D_t. If the renewable power being produced by the HES is greater than or equal to the block's total electricity demand $P_{HES_t} \geq D_t$ then it supplies power to the homes on an equal basis based on the power production available at any one time, without the need to draw power from the utility grid. If not then homes take the same power from the HES independently of their consumption and buy from the grid to meet the rest of their power demand which cannot be satisfied by the HES. In this case, the power to be supplied by the utility grid to each home at time t is given by its demand at time t minus the fraction corresponding to the total power produced by the HES divided by 15 (the number of houses comprising the sustainable block). $P_{home_{it}} = d_{it} - (P_{HES_t}/15)$. The next condition states that if the time of having to purchase from the grid is equal to the average time for house i having to purchase power (how much time on average was power purchased from the utility grid). If yes, then the power to be purchased for the month (computed for each

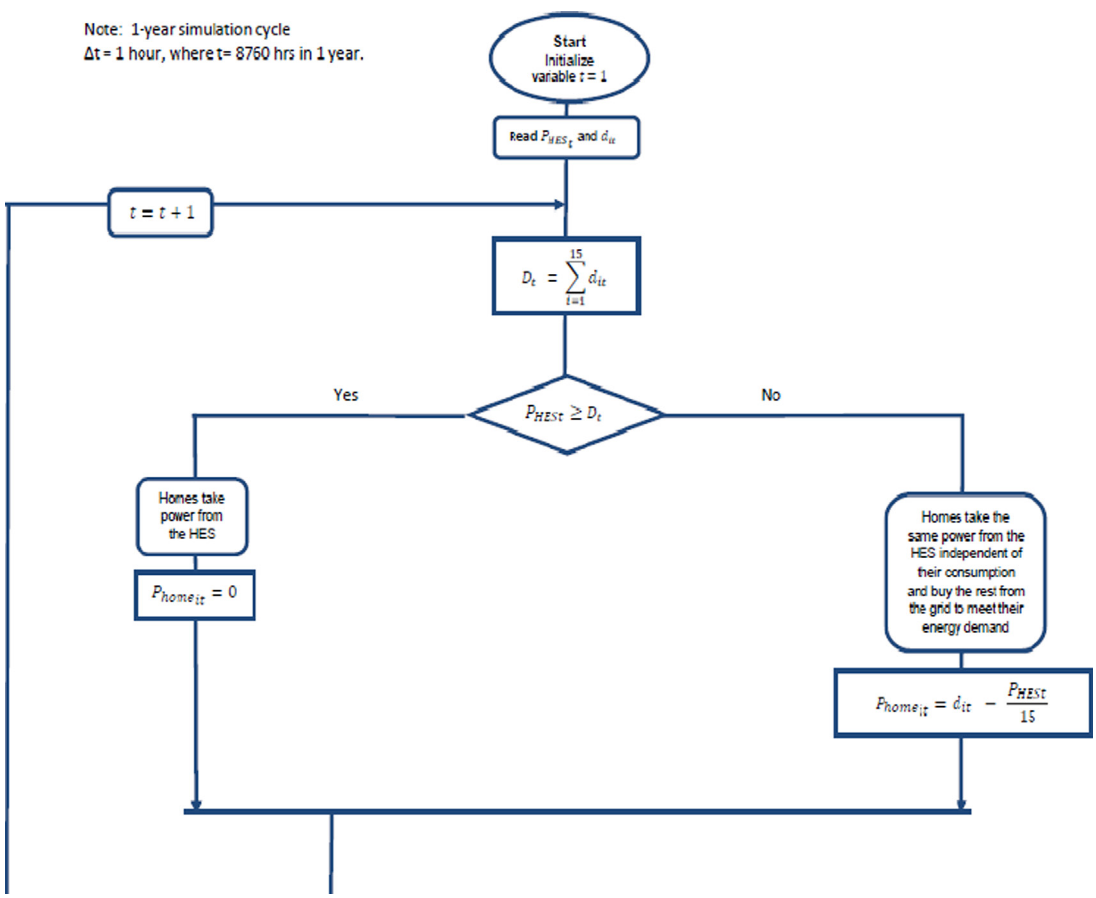

Fig. 4. Above it is shown the first half of the flow diagram for criterion 0, the simplest of the five.

house and for the entire block) is $\overline{P}_{im} = \sum_{\bar{t}_{m-1}}^{\bar{t}_m} P_{home_{it}}$. If no, then the control repeats the loop until power supply is fully assigned to the homes. For the yes case, a rule of merit is used as indicated by the lower part of the diagram, which establishes a threshold for the treatment of the cost to be paid by the house as shown in Fig. 5.

$$\overline{P}_{im} < 75 \text{ kW h}$$

If the power being consumed by the house is less than a threshold which is the case of our simulation based on the consumption of a hypothetical small community in Chile is 75 kW h per month, then the cost is practically zero as the homes that consume so little power are entirely subsidized by the homes that consume more than that threshold level. The two different cost computing structures upon which the cost of electricity consumed is calculated, following the decision block yes or no stage, reflect the different rates that apply to each consumption range by the utility grid supply for the particular location in which the small community resides. The simulation ends for $t=8760$ h in a year.

Next there is criterion 1, which is basically the same criterion as zero but in this case homes take power from the mains and from the HES proportionally to their consumption, whereas in criterion 0 the homes take the same power from the HES independently of their consumption, and renewable power is distributed evenly among the 15 homes. Thus they must buy from the grid to satisfy the rest of their power demand. The cost function is the same for both. Then there is criterion 2. In this particular case a new condition is introduced, where the average power consumption of the sustainable block: $\bar{x} = D_t/15$ is to be used as a parameter against which the consumption of each home being read by the microgrid control system. Again looking at the first condition to be met, where it is asked if the power being produced by the HES at time t is sufficient to service the entire block's demand, $P_{HES_t} \geq D_t$. If this is met then homes can take renewable power from the HES as before. If not then another condition must operate in this case, since there is not enough renewable power being produced for whatever reason, so that the entire sustainable block faces the scarcity of the resource (limited or dwindling renewable power availability). Thus a greater demand than what the HES can supply obliges the supervisory control system to adopt a new condition which states that if the demand for power by home i at time t being read by the control system is greater than or equal to ($\geq$) the average consumption for the 15 homes $\bar{x} \leq d_{it}$ then home i must take power from mains. If its consumption is less than the average value, then $home_i$ takes power from the HES. Immediately it follows that if $P_{HES_t} \geq SUM$ where $SUM = \sum_{i=1}^{N} d_{it}$ then the house i does not have to buy power from the mains—that is $P_{home_{it}} = 0$. Otherwise the control system will exercise the same function as before, namely that $P_{home_{it}} = d_{it} - [(d_{it}/SUM) \times P_{HES_t}]$. This function is also used throughout the whole set of criteria. Hence, the power to be purchased by the home from the main grid this time will be based on the size of its power consumption at time t with respect to the SUM for the entire block. This suggest that a merit criterion based on proportionality operates here seeking to influence and somehow condition the energy consumption behavior for the benefit of the community where the energy users in their homes are required to make a small reduction in the amount of energy used in a way that incentivizes

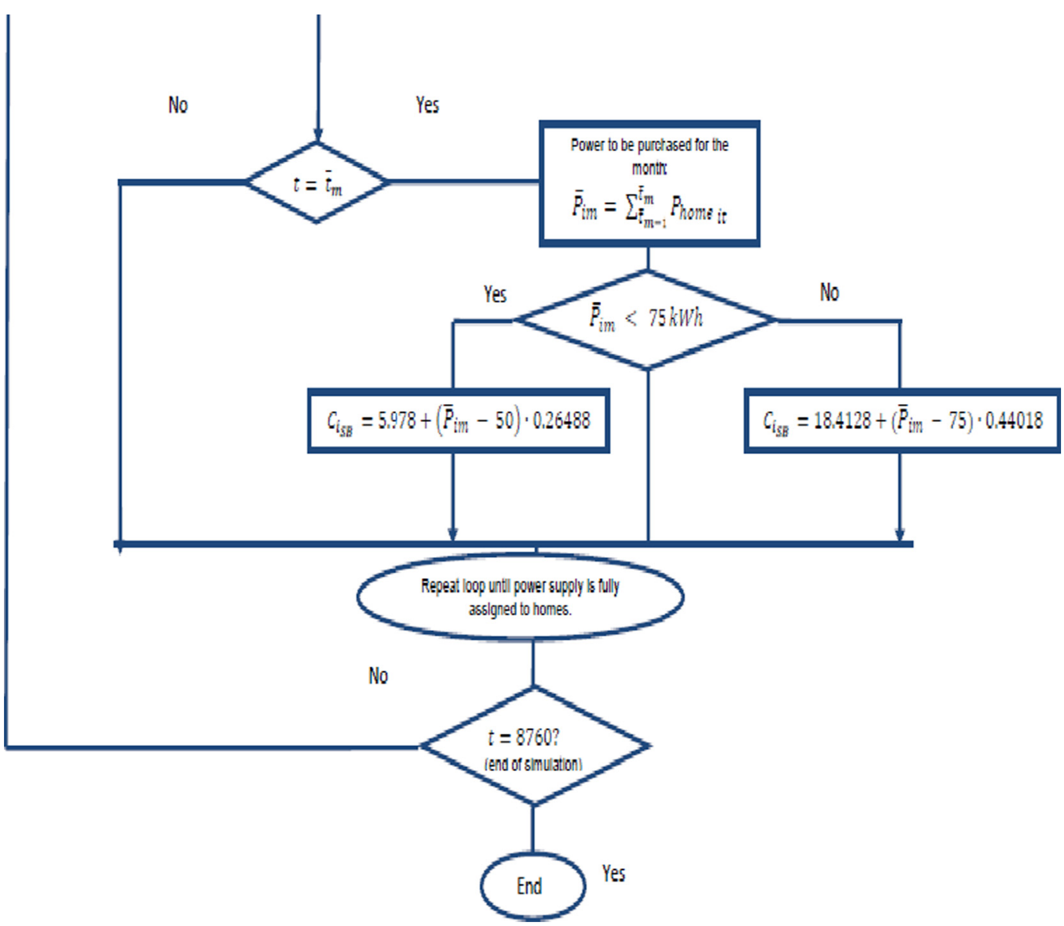

Fig. 5. Above it is shown the second half of the flow diagram for criterion 0, the simplest of the five.

a more efficient and thrifty consumption for the whole reaping the benefits as a collective as well as individual users. This behavior emulates cybernetics and homeostatic mechanisms operating in all living organisms that – as complex adaptive systems – can regulate their behavior in order to moderate their energy expenditure and become more efficient. This is coherent and in line with the conditions being imposed by a particular situation that may be affecting the power generation capacity of the HES and its power supply flow to the homes in the sustainable block [7–10,12,13].

Below is Fig. 6 showing the first portion of criterion 2, one of the five different algorithms each of which represents a particular criterion to be employed in the control strategy. The second portion is the same for criteria 0, 1 and 2 so it is omitted here as it was already shown above for flow diagram of criterion 0.

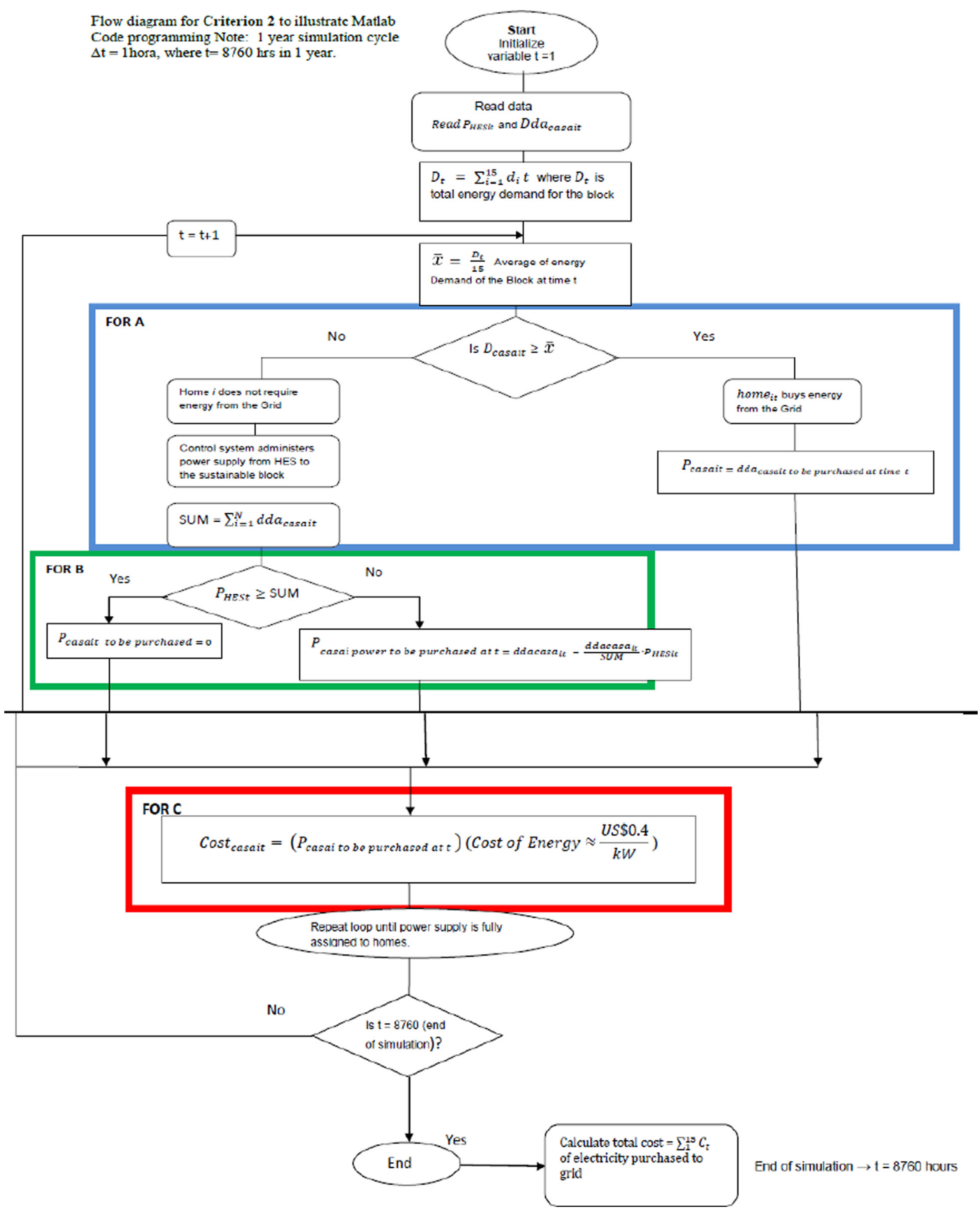

Fig. 6. Above is the flow diagram showing the first portion of criterion 2. The second portion is the same for criteria 0, 1 and 2 so it is omitted here as it was already shown above for flow diagram of criterion 0.

Criterion 3. Here one starts off with the same logic as in criterion number 2, with an average value of electricity consumption $\bar{x} = D_t/15$ defined as the average power consumption of the sustainable block; Next step in the algorithm is to average electricity consumption for the 15 homes in the block. Then the electricity demand of each home is compared to this average consumption $\bar{x}$ but then a specific eligibility range is set (considering the energy consumption habits of the particular community) with two bounds $\bar{x}_{lower}$ and $\bar{x}_{upper}$ with respect to the average value of electricity consumption in the sustainable block $\bar{x} = D_t/15$. Thus here there is a lower rank and an upper rank $\bar{x}_{lower} \le d_{it} \le \bar{x}_{upper}$ within which the energy demanded by each home must lie if it is to be considered an efficient and thrifty consumption within the block. Therefore if the energy demand of a particular home is within this range then it is eligible for renewable power supply from the microgrid, provided that there is sufficient renewable power being produced by the system. Thus if the condition is met $home_i$ takes power from the HES and if condition is not met, $home_i$ takes power from the utility grid. Cost is then computed based on the amount of power consumed by each of the homes. In addition, the algorithm takes into account the entire block's renewable power consumption and also the power purchased by the block from the mains. The more power purchased from the mains, the higher the cost, and the less thrifty an efficient the system is based on a given power supply regime from the HES.

Below is Fig. 7 whose flow diagram shows the first portion of criterion 3. The second portion is very similar to that of criterion 4 shown next. Thus it is omitted for the sake of brevity.

Next there is Criterion 4 shown in Fig. 8. In this last criterion – the most elaborate of the four – there is a specific condition set up which states that if the demand of a home $0.X \ \text{kW} \le d_{it}$ is greater than or equal to a certain value to be predefined for the control system monitoring, then the house is or is not eligible to receive renewable power from the microgrid. However, unlike the previous cases, here a further condition is introduced for the purpose of enhancing the regulation mechanism by the systems involved and this is done by the cost calculation but this time in regards to the average time of power being purchased by home i from the main grid, as it is shown in the flow diagram right below.

Here the amount of electric power purchased during a whole month from the mains by home i is computed by the summation $\bar{P}_{im} = \sum_{\bar{t}_{m-1}}^{\bar{t}_m} P_{home_{it}}$. Then there is a condition being set by the coordination and control system strategy, represented by the algorithm being employed, for the purpose of assigning RP supply to the homes in the sustainable block. This condition states that if power consumption by home i is less than or equal to a certain threshold or boundary limit (e.g. 75 kW h for a tiny community with low energy needs as in this particular case), that is $\bar{P}_{im} < 75 \ \text{kW h}$ then if Yes, condition is met and the cost function

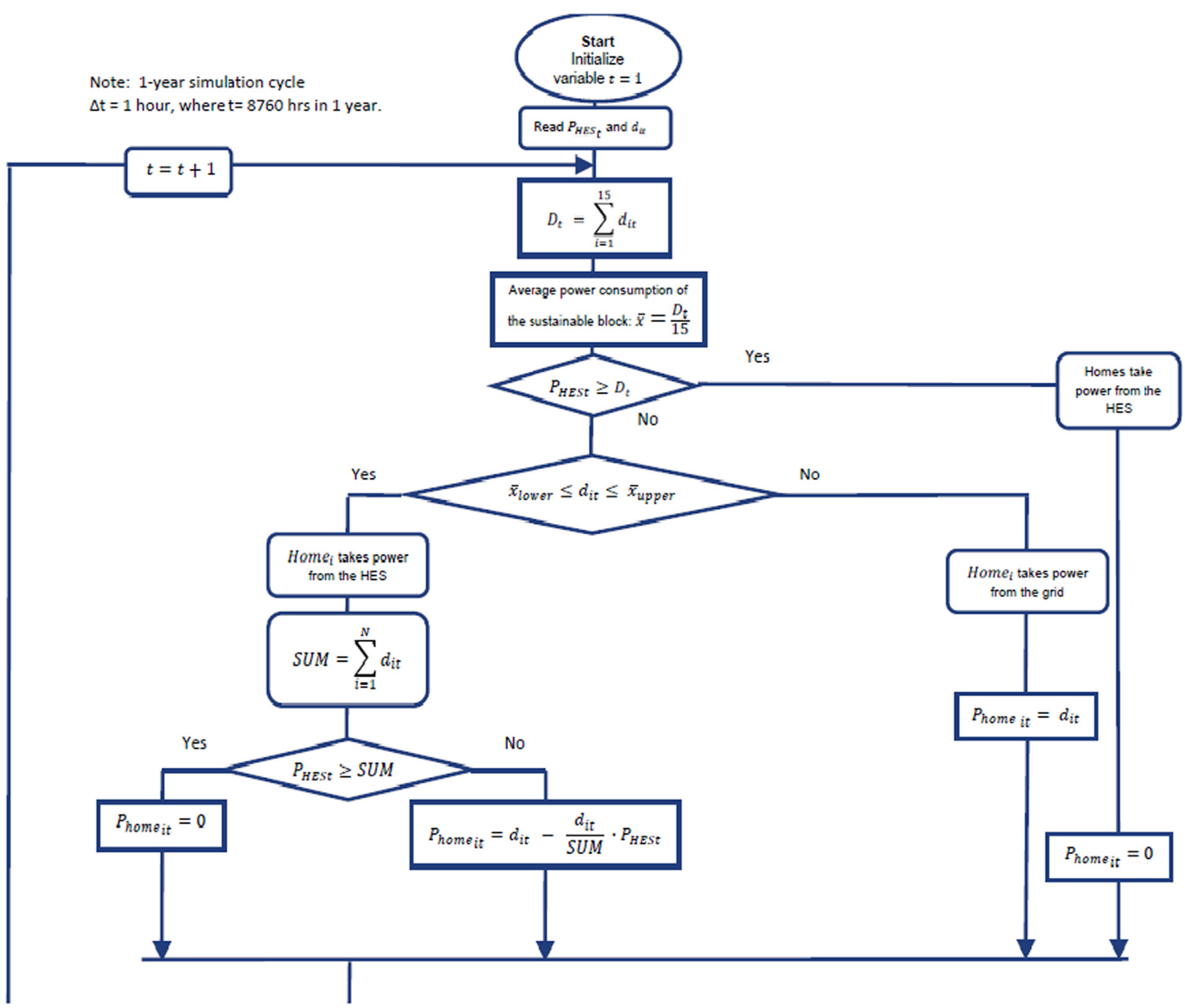

Fig. 7. Above is the flow diagram showing the first portion of criterion 3. The second portion is very similar to that of criterion 4 shown next. Thus it is omitted for the sake of brevity.

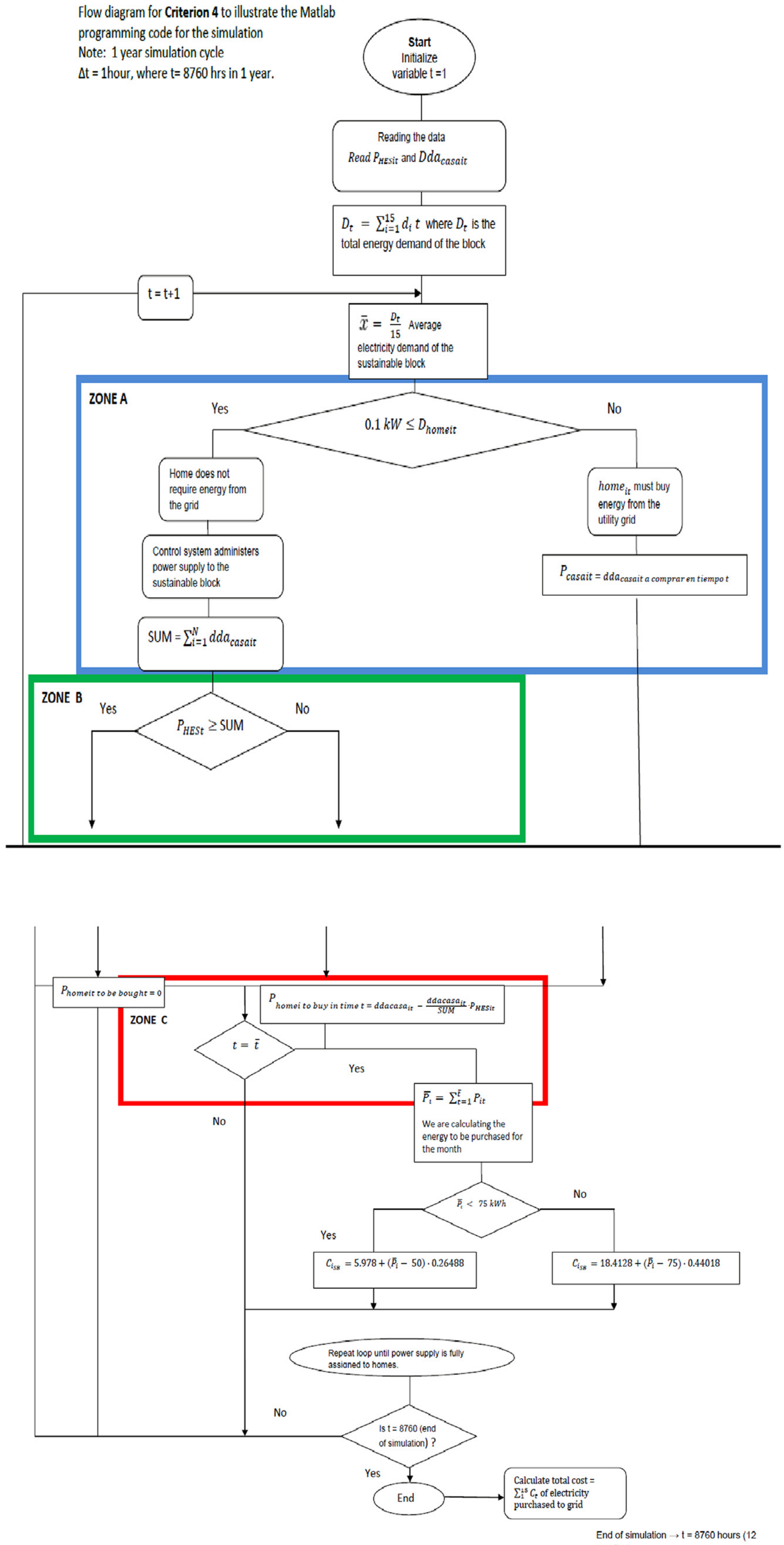

Fig. 8. The entire flow diagram of criterion 4, the more complex and elaborate of the five.

will determine that the house pays nothing at all as it is being subsidized by those homes which consume over that limit. Thus there is a merit mechanism based on consumption range specified in the criterion that fosters and elicits thrifty, efficient electricity consumption in the community, and rewards the homes that consume less than a certain borderline or threshold amount. Such

an amount must be carefully studied and its range of variation analyzed for a particular community based on historical energy usage data and specific energy consumption habits therein. This way the strategy seeks to keep cost reasonably low for the block while keeping the meta-system sustainable from the power generation and supply standpoint, as opposed to looking at it only from a demand side management perspective.

The cost functions and values used here are just an example which illustrates the example shown for simulation purposes with regard to a particular location scenario. These cost functions can be designed in a wide variety of ways using different cost-benefit schemes and pricing strategies, all of which may vary significantly from one place to the next, as there are very distinct energy users and various rates and pricing schemes being used by utilities everywhere, as well as by smaller suppliers using hybrid DG systems for electricity production. It will depend on a variety of factors, such as the location, time of year, size of the population, cost and means of electric power production, transport and transmission costs, etc. Yet the basic idea that the coordination and control strategy applied here is seeking to convey, is that restraining consumption (being energy efficient or thrifty in the use of electricity) is worth merit and must be rewarded as it is done in other industries with commodities like natural gas, for example. This particular criterion says that the microgrid will supply and charge for renewable electric power to the homes based on a certain threshold or boundary limit of electric power consumption, which is considered thrifty and efficient in terms of electricity consumption for this particular community.

Next there is the second half of criterion 4 shown in Fig. 9 with a variation introduced in the lower part for computing the cost of the renewable power supply from the HES.

In this portion of criterion 4 shown below, used as an example, there is yet another condition for costing which says that the cost of renewable electric power $C_R = \sum_{i \in M} C_{im}$ for the month is summed up for home i and then asks if home i is within M, where M denotes the set of homes with a monthly energy consumption which is less than 75 kW h. This is illustrated in the diagram portion below. In one case the total cost of electricity for house i is zero where in the other case the cost for the house is based on how much renewable power consumption it had for the given month.

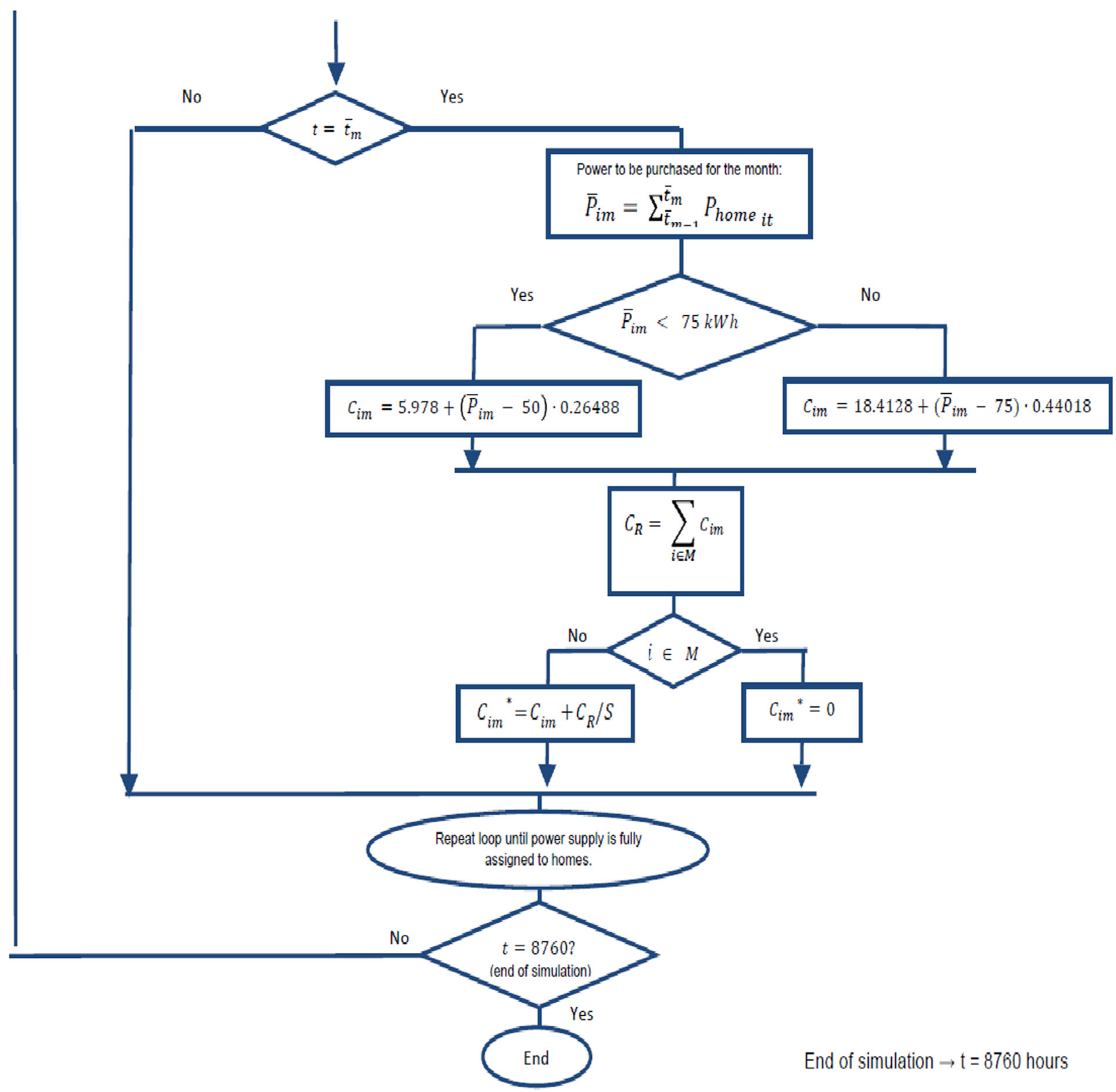

Fig. 9. Above is the second half of criterion 4 with a variation introduced in the lower part for computing the cost of the renewable power supply from the HES.

3. Results analysis of different scenarios and strategies based on the predefined criteria

Essentially a good amount of data was gathered in order to simulate both, the power supply generated by the HES and the kW h being consumed by each of the 15 homes which make up the sustainable block. These data were then run using Matlab 2010 in a simulation phase that used the total number of hours for a one-year cycle, that is $t=8760$ h in 1 year. Simulation was done for a grid-connected PV-wind micro-generation system operating without energy storage in this particular case and conditioning the supply of renewable power to the homes in the sustainable block based on the degree of thriftiness and energy efficiency of each home at time t for 8760 h in a full-year simulation run [8–10]. As mentioned before, simulation used real data from electricity consumption of residential consumers of a typical small community in Chile. This conditioning was implemented from the standpoint of the limited renewable power supply to the homes based on specific criteria designed to keep the energy intake and expenditure of the sustainable block (in essence a socio-technical system) aligned and compatible with the renewable power (RP) supply from the microgrid. This way the consumers will strive to keep their energy consumption low and be energy efficient in terms of accessing the changing renewable power supply availability from the microgrid, in a way that maximizes energy intake and efficient expenditure. This is being rewarded based on merit by assigning inexpensive RP supply to those homes that can maintain the habit of being thrifty and sustainable for the benefit of both the individual homes and of the whole block (collective benefit) as well. The other homes that consume more and thus depart from the energy homeostasis control action that makes the whole block more sustainable, must therefore buy their electricity from the main grid, at a much higher price than what RP costs. The results indicate that maximizing the system overall efficiency while minimizing system cost is a multi-objective optimization problem and clearly some criteria work better than others towards this end.

Upon analyzing the case for Evaluation 1 and 2 scenarios, each evaluation was done considering a high-difference scenario and a low-difference scenario with respect to the base case already explained earlier. Evaluation 1 corresponds to the simulation run for three distinct scenarios – low, medium and high – with respect to the difference among the electricity consumption of the 15 homes in the block. Again, the three scenarios tested are base-case scenario, high-difference (scenario 2) and low-difference (scenario 1) cases as explained. Next there is a graph shown in Fig. 10 with the annual cost per home in US$ for the sustainable block with criterion 0 for the 12 months (8760 h) under low, medium/base, and high case scenarios.

Evaluation 2 in turn corresponds to the same different scenarios as Evaluation 1 but with respect to different average consumption for the 15 houses in the sustainable block. That is, the data in Evaluation 2 uses a different set of values pointing to a variation in average consumption of users to make simulation realistic. Thus here there are a base scenario, a low-average difference (Evaluation1) and a high-average difference (Evaluation 2). Simulation was run evaluating each of the 5 criteria employed for each of the three case scenarios already mentioned for Evaluations 1 and 2. The simulation analysis seeks to show that it is possible – at least in theory – to attain a collective cooperation by means of recursive, continuous interactions among the different systems, as they adapt and arrive at a sustainable energy solution for the entire system – the meta-system – through emergence and co-evolution. The sustainable block of 15 homes is connected through a parallel network to the microgrid in order to receive RP from it as well as electricity from the utility grid which in turn is connected to and coordinates with the microgrid. These are all complex adaptive systems which comprise the meta-system under study. The simulation results are shown as follows along with their corresponding analysis and lessons learned from each case therein. First results are presented along with the analysis with respect to the base case scenario (or medium case). Let us remember that a base case scenario corresponds to a set of power supply and demand data which was established using the average value of power supply from the HES to the homes, the average value of energy demand based on consumption patterns from each of the 15 homes of a particular remote community in Chile. This average or medium case scenario is used as the basis upon which to base the comparison with the other two cases studied.

Next there is Tables 1 and 2 which compares the cost results of the five criteria employed and also right underneath there is Fig. 11 which shows the cost-benefit analysis and results for individual homes and for the entire sustainable block based on the different criteria utilized for base case scenario

The graph above shows the different costs incurred by each home under the different criteria employed for the simulation run on the 15 houses comprising the sustainable block. Here one can see that the worst results are obtained with criteria 2 and 3 while criteria 0, 1 and 4 give better results for most of the homes, particularly 1 and 4. This suggests that a better, more efficient solution can be worked out with regard to these three criteria rather than with the other two. Next there is Fig. 12 which shows the total electricity cost (in US$) of the sustainable block for each of the 5 criteria employed under base case scenario in the simulation and the last one with no hybrid energy system (HES).

Here one can see that for the base case, criteria zero and one work better than the rest and of course, the worst case scenario is the block without HES, and having to purchase all their electricity

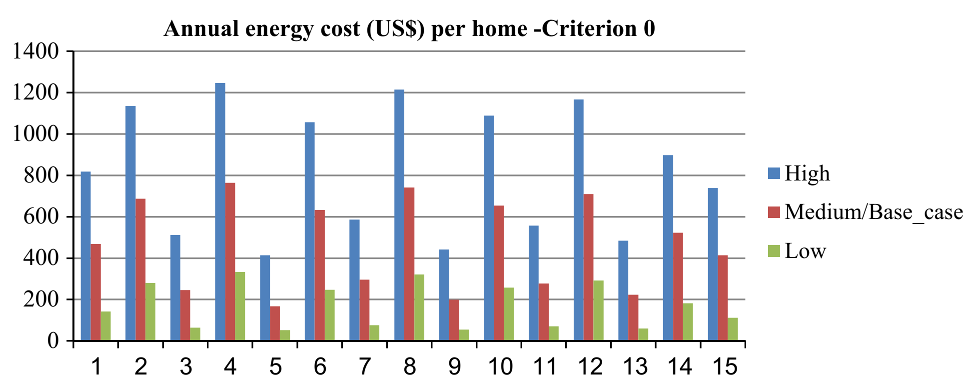

Fig. 10. Annual cost per home in US$ for the sustainable block with criterion 0 for the 12 months (8760 h) under low, medium/base, and high case scenarios.

needs from the utility grid. In fact criterion 1 proves to be slightly better yet than criterion 0 showing that for this criterion a better, more efficient solutions in terms of cost-benefit is obtained for the entire block.

Evaluation 2 as stated already corresponds to simulation run for the three different scenarios with respect to the different average consumption of the houses in the sustainable block. Thus here a base scenario, a low-average difference (scenario 1) and a high-average difference (scenario 2) are used and simulation is done for the different criteria under the three scenarios. The results obtained for just about every criterion indicate that only for low and medium difference in homes average consumption, the costs are low. Otherwise, when dealing with high average consumption, this particular set of criteria is not a good strategy to use to bring about efficient and sustainable energy consumption within the sustainable block.

Finally, and just as a remark, one can see that although far from optimal, criteria 0 and 1 again seem to show better results than the other three, but as it was said before, only when difference is in the low to medium range in homes average consumption. The reason why criterion zero is used as an indicator, and shown here as a separate yardstick or benchmark if you will, is because by reason of its very nature, it is considered here as ground-base criterion representing a basic, generalized case. Let's remember that criterion 0 is a very basic, plain criterion where the power demand of the entire block is added up and then compared to what the HES is producing at any point in time. If the renewable power being produced by the HES is greater or equal to the block's total power demand $P_{HES_t} \geq D_t$ then it supplies power to the homes on an equal basis based on the power production at any one time, without the need to draw power from the utility grid. If not then the homes take the same power from the HES independently of their consumption and buy from the grid to meet the rest of their power demand which cannot be satisfied by the HES. Next there is Fig. 13 showing the performance of criteria 0 to 3 in terms of the annual cost incurred by the sustainable block in US$ of the sustainable block for 12 months (8760 h) period Fig. 14.

Below is Table 3 with the annual cost of criteria 0 to 3 and Table 4 with the total cost for the sustainable block under criterion 4, the best results were obtained with this choice.

Below there is Fig. 15 which shows the cost (in US$) versus the value of the parameter X in criterion 4.

Below there is Table 5 where the five different criteria are compared for the three scenarios simulated.

Below there is Table 6 with the general results of the average residential electric bill savings (in US$) for the 15 homes in the block. Right underneath Table 6 there is Fig. 16 that shows the monthly cost per home for each month and the savings as a portion of the total cost—average annual savings on electricity cost per home: 912.98 [US$].

Table 1
Below is a simple differentiation per consumer type which summarizes the category classifying scheme behind the reward-based renewable power (RP) supply control strategies proposed.

Reward-based renewable power (RP) supply and consumption differentiation strategy	
Consumer type	**Power supply criteria**
Thrifty consumption	Low-consumption, high-reward aimed user type by consuming all renewable at very low price, thus allowing more RP to be available for the rest of the block
Middle of the road	Efficient, reward-aimed but also takes power from the grid
High consumption	Low renewable power or non supplied, depending on consumption range. User is not really interested in savings and RP

4. Discussion

Homeostatic control was, according to Schweppe et al. [1], based on two major principles: (1) utility-customer interaction and cooperation and (2) the independence of the customer in his decision making process with respect to power supply and consumption to seek the most viable and most benefit-yielding alternative for his/her electricity supply band consumption scheme. They basically

Table 2
Total cost per year for the sustainable block (15 homes) tested under 5 distinct criteria and No HES.

Total Cost (in US$) for the sustainable block for the year					
Criterion 0	Criterion 1	Criterion 2	Criterion 3	Criterion 4	No HES
7002.97	6983.12	8971.11	8002.62	7117.11	17,615.77

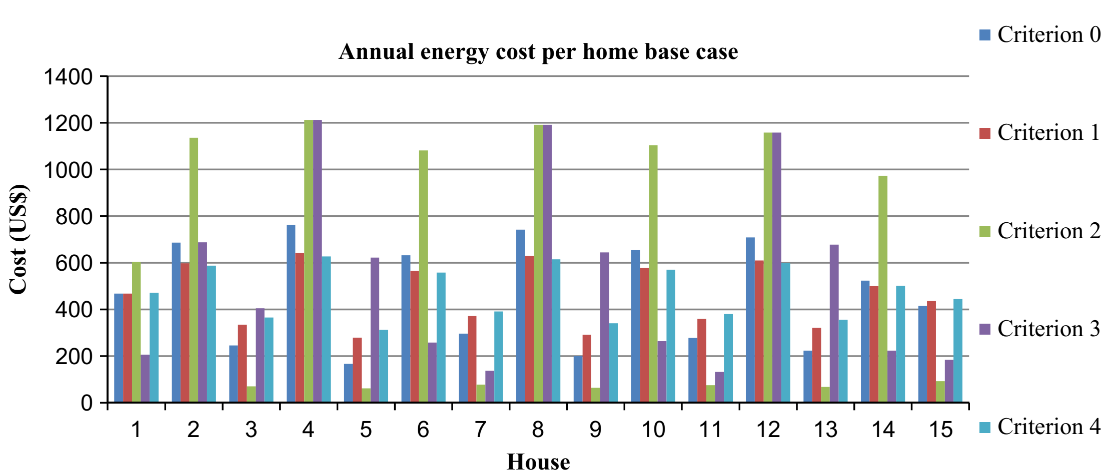

Fig. 11. Cost-benefit analysis and results for individual homes and for the entire sustainable block based on the different criteria utilized for base case scenario.

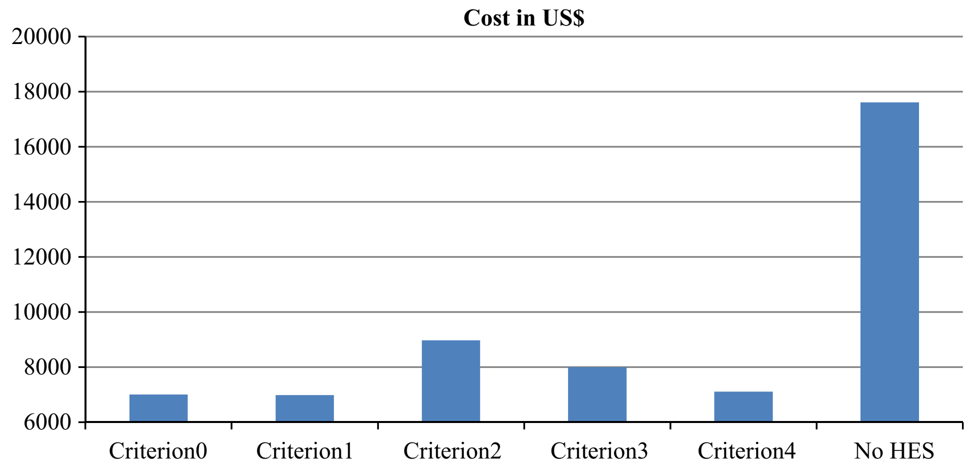

Fig. 12. Above there is a graph showing the total electricity cost (in US$) of the sustainable block for each of the 5 criteria employed under base case scenario in the simulation and the last one with no hybrid energy system (HES).

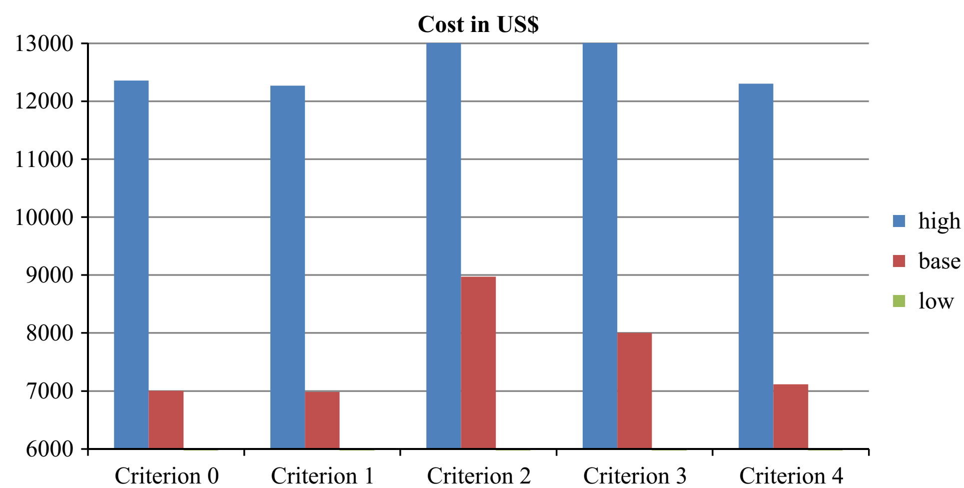

Fig. 13. A view at the different criteria's performance this time showing the annual cost in US$ of the sustainable block for 12 months (8760 h) period under the low, medium/base, and high case scenarios. Criterion 4 results are shown below in Fig. 14.

Table 3
Above the annual cost of electricity consumption for a sustainable block under Evaluation 1 scenario.

	Criteria employed			
	Criterion 0	**Criterion 1**	**Criterion 2**	**Criterion 3**
High	7245.34	6935.11	9787.14	11,109.41
Medium/base case	7002.97	6983.12	8971.12	8,002.62
Low	7008.2	7008.2	8574.14	7,025.5

Table 4
Total cost for the sustainable block under criterion 4, the best results were obtained with this choice.

Total cost_in US$_for_sustainable block in one year			
Criterion 4 (0.2 kW)	Criterion 4 (0.1 kW)	Criterion 4 (0 kW)	Criterion 4 (0.4 kW)
7046.58	6932.58	6935.12	8508.52
7117.1	6986.06	6983.12	9225.45
7143.99	7029.37	7025.5	9670.59

argued that it was to the advantage of both the customers and the utilities that a more cooperative, proactive and helpful relation between the two were allowed to exist, and that somehow a dynamic co-evolution of interests and perspectives of both parties should be permitted to emerge. Such an approach sought to conciliate both sides posture for the benefit of the industry and the community as a whole. This meant a regulatory and technological scenario not yet in existence back in those days. One where the customer could communicate with and be informed by the power supplier at any time through what is known today as smart metering, allowing the customer to have more decision making power instead of grandfathering and deciding for them all the time without having the possibility of being a relevant player as well [1–6]. In light of the above it is relevant to recap the basic ideas behind the model presented here. The paper seeks to revisit HC principles and explore an alternative angle of the HR concept in living organisms applied to EPS as Schweppe and his team did, but putting it in the context of the many challenges facing micro-generation power systems today and their integration with the main grid; a reality which was still in its infancy back in Schweppe's time over 30 years ago. Things have changed of course, yet at a slower pace than expected – energy efficiency being a telling example of this much slower-than-expected change – and now society is at a crossroads where it needs to advance in mini and micro-generation systems integration and in energy efficiency (EE) as both go hand in hand. Hopefully this time EE for residential purposes – coupled with a

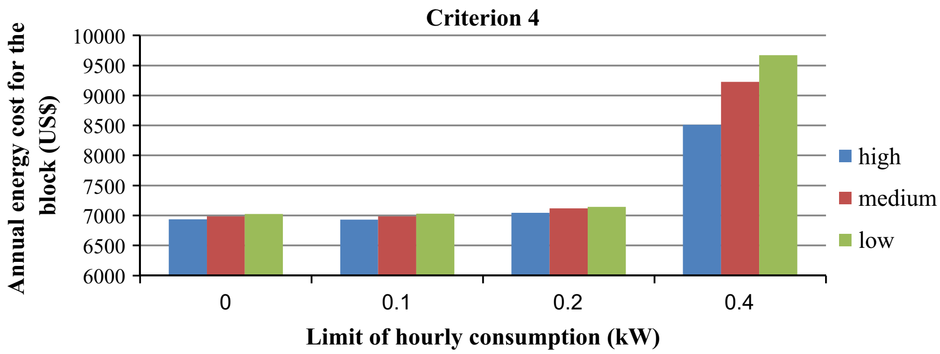

Fig. 14. Cost performance for the entire block with criterion 4 with different values of X under the scenarios

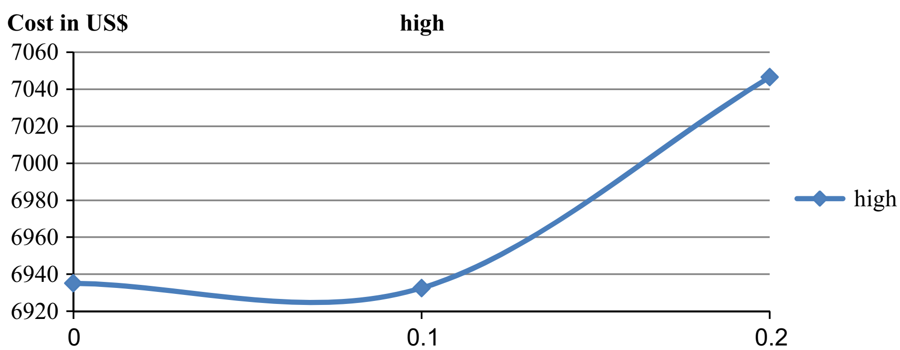

Fig. 15. The graph above indicates cost (in US$ on the y-axis) versus value of X. The best values for criterion 4 were obtained with a value for X close to 100 W or 0.1 kW. Results above (Tables 3 and 4) were obtained under Evaluation 1. Again a better result is obtained for a value of X closer to 100 W but no less than that. A value for X between 100 W and 200 W is also an alternative to thrifty, efficient energy consumption for the block.

Table 5
Annual cost (in US$) of electricity consumption for the sustainable block under Evaluation 2 scenario.

Scenario	Criterion 0	Criterion 1	Criterion 2	Criterion 3	Criterion 4
High	12,357.33	12,270.24	14,420.7	13,558.32	12,304.96
Base	7,002.96	6,983.12	8,971.12	8,002.62	7,117.11
Low	2,543.1	2,270.36	4,356.88	3,425.52	1,980.23

Annual cost (in US$) of electric power consumption for the sustainable block.

Table 6
The general results of the average residential electric bill savings (in US$) for the 15 homes in the block are presented above for a 12-months period, with average total annual savings per home in the sustainable block: US$ 913.00.

	Average monthly home electricity consumption [US$]		
	Without HES	With HES	Savings
January	134	61	73
February	142	66	77
March	129	59	69
April	126	64	63
May	125	51	74
June	135	71	64
July	124	60	64
August	135	47	88
September	142	59	82
October	121	44	77
November	137	44	93
December	142	53	89
Total	**1592**	**679**	**913**

genuine sense of thriftiness – will move at greater strides than it did in the past, when it fell far behind DG especially in the context of technical and operational issues as opposed to social, economic, regulatory and environmental ones, when compared to microgrids, as proven in the last 15 years. Likewise, in order to take full advantage of the benefits of DG and NCRE integration in the current highly centralized power systems infrastructure, there are certain strategies which can be used effectively. Just like HC principles assertively state, such strategies must have the supplier(s) and the customers (loads) interact as active players in a continuous dynamic exchange so as to be able to find a common ground that benefits both parties as a whole meta-system in the long run. Hence by accepting this premise it can be shown – at least in theory – that a viable option is possible and even desirable; which proves successful at approaching both – load (demand) management and energy efficiency – by incentivizing demand curtailment by means of customers efficient, thrifty electricity consumption. This is not only possible but necessary in the authors view, and should be considered whenever looking to integrate micro-generation systems to the grid, especially in the absence of very expensive energy storage systems. To do this one may apply the merit-rule approach exemplified here, using strategies that are reward-based to assign a limited resource – a scarce commodity such as renewable electric power supply – using a set of predefined criteria which aim at achieving efficient, sustainable electricity consumption within the community. Such strategies make it possible to assign a scarce/limited resource such as RP provided by the microgrid which varies randomly at times, as an alternative to the expensive utility grid power supply and, at the same time, to achieve higher levels of EE that can yield the most benefit and ensure sustainability for the meta-system in the long-run.

In regards to the future of SES, one final thought comes to mind that will hopefully elicit further contributions by other authors, enriching the subject's discussion. When thinking about sustainable energy systems in general and in HMS supplying power to small-size communities in particular, one must never lose sight of the appropriability concept at play and its link to a productive and sustainable energy scenario for such communities. Just as

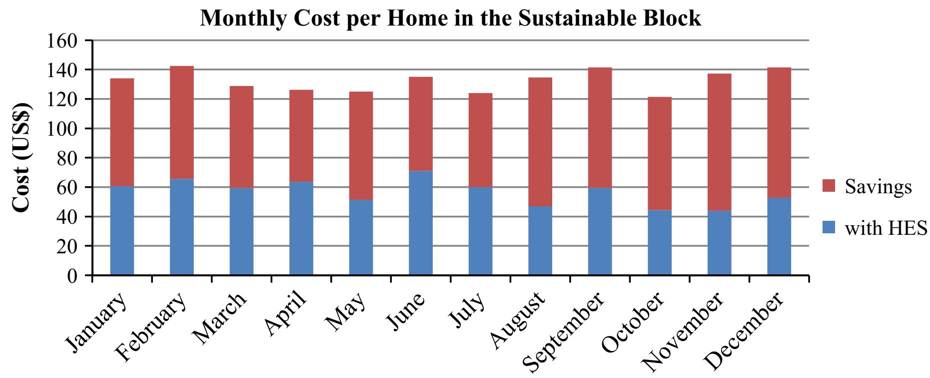

Fig. 16. Above it is shown the monthly cost per home for each month and the savings as a portion of the total cost—average annual savings on electricity cost per home: 912.98 [US$].

economists point to factors of production to explain economic growth and prosperity in a certain industry, or the factors that govern an innovator's ability to capture profits generated by an innovation, so it is with sustainable energy systems (SES) and stakeholders. Here the term appropriability is quite pertinent in the subject's discussion and should come into play in full force, as a strong attractor and motivator of stakeholders. One must understand that people of every walk of life are motivated first by their own benefit, essentially by greed not by good intentions or idealism—not even when it comes to clean energy, Carbon footprint reduction and a sustainable society. Thus an adequate formula for allowing appropriability of the system's operation and for reaping its benefits therein is that such a concept be taken fully into account, as a crucial part of the planning and implementation of SES. Hence one needs to look at the economic factors of energy sustainability and energy efficiency and how to make the marriage of these two work best when designing and operating the system. This is necessary in order to ensure the successful integration of HMS with the current electric power infrastructure (the grid) and their technical and operational sustainability in the long term.

5. Conclusions

In this paper DG solutions and hybrid micro-generation power systems are examined for the particular case of a HES without energy storage connected to the grid and supplying power to a set of residential customers termed a sustainable block [9], treating it as an integrated system. Analysis was done with simulation of the system evaluating what may happen in such systems as particular strategies are applied like the one being proposed here for the purpose of eliciting EE, thriftiness and energy sustainability. Such strategies can be implemented in the supervisory control system of the grid-tie microgrid for the coordination and control of such systems as they become more widespread and integrated with the current electric power infrastructure with which it comprises a meta-system. The argument presented here is that such systems may be treated as dynamically complex living organism, essentially CAS capable of co-evolution and adaptation, and as such are subject to homeostatic regulation. When humans are involved they may also be studied and analyzed as socio-technical systems, equally complex in nature as other living systems. Such systems continuously interact with their environment seeking to regulate and adapt their energy production and expenditure as needed.

Given the fact that a HMS consists of two or more RES, this has the advantage of more stability and flexibility, both key properties of such systems and their configuration as was already discussed. Collected data of the various energy sources was duly analyzed in order to plan for the configuration and sizing of the system simulated. A hybrid grid-connected microgrid without energy storage, supplying power to a group of homes was modeled and simulated. A homeostatic control strategy comprising five distinct criteria for controlling power supply to residential consumers of a small community was employed and duly analyzed. Systems simulation under different scenarios was done testing for thriftiness, EE, and energy sustainability and – upon changing power supply in different scenarios – certain criteria worked better than others showing that they are more suitable for particular scenarios and consumption habits. The approach used here aims to reconcile power supply and demand response management towards energy sustainability (ES). Simulation results show that it is possible to do both: to instill EE and thriftiness in the target community as well as to achieve higher flexibility in the system overall by embracing energy demand response and power supply control management strategies to create true sustainable energy systems.

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